Market-mediated responses confound policies to limit deforestation from oil palm expansion in Malaysia and Indonesia

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The global demand for palm oil has grown rapidly over the past several decades. Much of the output expansion has occurred in carbon- and biodiversity-rich forest lands of Malaysia and Indonesia (M&I), contributing to record levels of terrestrial carbon emissions and biodiversity loss. This has led to a variety of voluntary and mandatory regulatory actions, as well as calls for limits on palm oil imports from M&I. This paper offers a comprehensive, global assessment of the economic and environmental consequences of alternative policies aimed at limiting deforestation from oil palm expansion in M&I. It highlights the challenges of limiting forest and biodiversity loss in the presence of market-mediated spillovers into related oilseed and agricultural commodity and factor markets, both in M&I and overseas. Indeed, limiting palm oil production or consumption is unlikely to halt deforestation in M&I in the absence of active forest conservation incentives. Policies aimed at restricting palm oil production in M&I also have broader consequences for the economy, including significant impacts on consumer prices, real wages, and welfare, that vary among different global regions. A crucial distinction is whether the initiative is undertaken domestically, in which case the M&I region could benefit, or by major palm oil importers, in which case M&I loses income. Nonetheless, all policies considered here pass the social welfare test of global carbon dioxide mitigation benefits exceeding their costs.

Malaysia and Indonesia | palm oil restriction | deforestation | economic impacts | market-mediated responses

Oil crop production has increased rapidly in recent decades and has shifted toward tropical areas (1). Among all oil crops, increases in production of soybeans and oil palm have been extraordinary. Between 1990 and 2016, the global production of soybeans increased by 226 million metric tons (MMT). A large share of this expansion (60%) occurred in South America. The global supply of oil palm increased by 240 MMT (53 MMT of palm oil) during the same time period. Most of this expansion occurred in Malaysia and Indonesia (M&I). More palm oil is consumed globally than any other vegetable oil. Palm oil is largely used in food products (71%) and is a major input in cosmetic products (24%). Only a small fraction (5%) of palm oil is used as an energy source.

Previous studies have examined the environmental consequences of these rapid changes in considerable detail. These papers (*SI Appendix, section 2*) highlight the losses of biodiversity and the release of terrestrial carbon due to tropical deforestation occurring in some of the most carbon- and biodiversity-rich biomes on the planet. In response to these concerns, voluntary and mandatory regulations were established to limit deforestation in these areas. To some extent, these efforts have limited the rate of deforestation in South America, particularly in Brazil, where livestock production and soybean expansion have been major drivers of deforestation (1, 2). However, deforestation has continued at a rapid rate in the M&I region (3). This has led to both governmental and nongovernmental regulatory actions seeking to limit the establishment of palm plantations on carbon-rich areas of M&I through domestic moratoria on the conversion of primary forests and peatland (4), as well as through the use of sustainability certification schemes (1, 5) (*SI Appendix, section 3*).

The attempts to limit oil palm-driven deforestation in M&I have fallen short of their stated goals, however, for several reasons. First, the overall share of certified palm oil in total palm oil supply is less than one-third, and certified areas often overlap (5). Second, most certified plantation areas hold little remaining forest. For example, the largest certified plantation program contains less than 1% of the residual forest area inside Malaysian oil palm plantations (6). In addition, laws and regulations related to land use are only as effective as their enforcement, which has been quite limited until recently (4). Therefore, palm plantations have continued to expand into carbon- and biodiversity-rich areas in M&I, leading to calls for new, more aggressive measures aimed at limiting consumption of palm oil, particularly for biofuel production. While there has been considerable debate in the public media about the pros and cons of such a ban (*SI Appendix, section 4*), to the best of our knowledge, no major effort has been made to quantify the economic and environmental implications of limiting consumption of palm oil produced in M&I. This paper aims to remedy this knowledge gap by providing a rigorous evaluation of the market-mediated consequences of restrictions on both the production and the consumption of palm oil. Finally, it is also

Significance

The rapid expansion of oil palm in Malaysia and Indonesia (M&I) has contributed to record levels of deforestation, carbon emissions, and biodiversity loss. Sustainability certification schemes seeking to address this problem have fallen short of their stated goals, leading to calls for more aggressive measures. Here we explore 3 alternative conservation policies within a global economic framework and find that market-mediated responses confound the efficacy and distributional impacts of these policies. We suggest that simply limiting palm oil production or consumption is unlikely to halt deforestation in M&I in the absence of active forest conservation incentives. We also find that M&I would benefit economically by taking domestic action rather than waiting for others to act.

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important to bear in mind that restricting the expansion of oil palm production in M&I might not in itself eliminate deforestation in this region, as palm plantations are not the sole driver of deforestation and drainage of peatland in this region (1).

Analysis of restrictions on the consumption of oil palm produced in M&I is complicated by the market-mediated effects that are expected to follow any significant intervention. To begin with, such an action could translate into additional demand for other oil crops. This might lead to crop switching and could even increase the demand for new cropland across the world as oil crop producers seek to replace the gap left by oil palm, which has higher yields than that of competing oil crops[1] (5). Such additional cropland conversion could itself generate land use emissions and biodiversity losses. However, it is also possible that biodiversity losses and carbon emissions from land conversion could be significantly lower if other oilseeds are produced on lands with less biodiversity or with low terrestrial carbon stocks (7–10). Larger terrestrial emissions can also result if land use moves to areas with relatively large carbon stocks. The net savings in land use emissions depends on where the land use change occurs. In addition, since these competing oilseed crops typically generate a large amount of oilseed meal as a by-product (the meal content of oil palm is very small compared with other oil crops, such as soybeans or rapeseed), and this meal represents a key ingredient in livestock feed, the replacement of palm oil with oils from meal-rich oilseeds such as soybeans is expected to increase the global supply of meals, thereby benefitting livestock producers who might now be able to produce more animal-based food products per unit of land (1, 11). Finally, by restricting global oilseed availability, we would expect to see a rise in the overall price of vegetable oils, thereby leading to a reduction in their consumption. In short, the market-mediated consequences of any major restriction on consumption of palm oil produced in M&I could have wide-ranging impacts on human and natural systems and thus merit more thorough investigation.

This paper uses a well-known medium-run Computable General Equilibrium (CGE) model to assess the global consequences of a major restriction on the consumption of palm oil produced in M&I. This model, GTAP-BIO (*SI Appendix, section 5*), has been widely used to study the economy-wide impacts of environmental, energy, water, and trade policies and their land use implications. To assess the potential medium-run impacts of limiting consumption of palm oil, a historical simulation and 3 policy experiments were developed. The historical simulation captures changes in the global economy over the period 2011 to 2016, during which significant changes occurred in the global markets for oil crops and vegetable oils. The total harvested area of oil crops increased by 29 million hectares (Mha) between 2011 and 2016, amounting to roughly 50% of the expansion in the global harvested area of all crops. Among the major oilseeds, the harvested area of soybeans increased by 17.7 Mha during this period, fueling an expansion in global soybean production of 73.5 MMT. Global production of soybean oil increased by ∼11.36 MMT between 2011 and 2016. In addition to soybeans, expansion in the harvested area of oil palm made major contributions to the observed expansion in the global supply of vegetable oils between 2011 and 2016. The harvested area of oil palm increased by 3.5 Mha over this time period, mostly in M&I. The observed expansion in area of oil palm is not large compared with the expansion in soybean area; however, since the per hectare oil content of oil palm is higher than that of soybeans, the observed expansion in harvested area of oil palm provided more oil than the corresponding area expansion in soybeans during the 2011 to 2016 period, when the global production of oil palm fruit and palm oil increased by 56.5 MMT and 14.37 MMT, respectively.

Our historical baseline simulates changes in the global economy over the 2011 to 2016 time period. To construct this baseline, we exogenously perturbed the GTAP-BIO model with observed changes in macroeconomic variables and allowed the model to endogenously determine changes in other variables, such as production, consumption, and trade of goods and services produced worldwide and their prices (*SI Appendix, section 5*). The model is capable of capturing important features of the global oilseed economy (*SI Appendix*, Figs. S3–S7), thereby providing a sound basis for analysis of restrictions on the production and consumption of M&I palm oil. To examine the medium-run economic and land use consequences of a major restriction on palm oil produced in M&I, 3 counterfactual policies were examined:

- Experiment I: Baseline combined with a regulation policy that freezes production of oil palm in M&I at its 2011 level via a domestic production tax (*TAX*).
- Experiment II: Baseline plus *TAX* supported by an economic incentive (subsidy) to freeze forest area in M&I at its 2011 level (*TAXAREA*).
- Experiment III: Baseline plus a uniform international tariff on the world imports of palm oil from M&I that freezes production of palm oil in this region at its 2011 level, along with the freeze on forest area in M&I (*TARIFFAREA*).

These policies highlight the differential impacts of alternative combinations of economic incentives to control the global consumption of palm oil produced in M&I and prevent deforestation. Two of these experiments focus the intervention on the supply side of the market, while the third experiment intervenes on the demand side. The first experiment, *TAX*, implements a domestic production tax over the baseline period, with the goal of freezing production of oil palm in M&I at its 2011 level, allowing other markets to adjust to the resulting changes in supply and demand for oilseeds, land, and other key components of the global oilseed economy. This policy effectively restricts global consumption of palm oil produced in M&I.

The second policy, *TAXAREA*, seeks to address the fact that, according to the existing literature, a restriction on the consumption of palm oil produced in M&I might not stop deforestation in this region (1, 5, 6). Therefore, *TAXAREA* adds, in addition to the production tax, an incentive subsidy to keep forest area in the M&I region at its 2011 level.

The first two experiments represent domestic initiatives in the M&I region to control oil palm production in this region, leading to less consumption of palm oil on a global scale. The third experiment, *TARIFFAREA*, depicts the consequences of the Rest of the World (RoW) taking action aimed at limiting consumption of palm oil produced in M&I. Specifically, this is done via import restrictions, achieved through bilateral tariffs on M&I-produced palm oil. These restrictions aim to achieve the same goal as the previous policies—namely, to freeze M&I oil palm production at 2011 levels. In addition, the M&I forest subsidy applied under *TAXAREA* is retained in the third experiment. Replacing the domestic forest subsidy with an international forest subsidy would provide similar land use impacts and enhance the economic gains for M&I, but would add costs for other countries.

Results

To capture the medium-run impacts of limiting the consumption of palm oil produced in M&I under each counterfactual policy, we compared the ensuing results with those obtained under the historical baseline. By way of example, cropland expansion in M&I is 79.59 Mha under the baseline and 79.23 Mha under *TAX*. We

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[1] In 2016, the value of oil plus meal for Malaysian oil palm and the value of US soybeans per hectare per growing day were approximately $8.15 and $6.35, respectively. Expressed in this way, the gap is smaller than the oft-cited figure of 5- to 8-fold higher oil palm yields compared with yields of competing oil crops.

report the difference between these 2 values (i.e., 79.23 − 79.59 = −0.36) as the net impact of the *TAX* policy on cropland area of M&I. To account for the uncertainty associated with model parameterization, we undertook a systematic sensitivity analysis for each policy to estimate a 95% confidence interval for each variable (*SI Appendix*, section 8).

Restricting Consumption of Palm Oil Produced in M&I Does Not Reduce Global Oilseed Area. *TAX* limits global consumption of palm oil produced in M&I via a production tax on oil palm produced in this region. As expected, compared with baseline, the restriction on production of oil palm reduces the harvested area of this crop in M&I by 3 Mha (Fig. 1, *Top Left*). In the absence of any economic incentive to avoid deforestation, the restriction on oil palm production encourages farmers to expand production of other crops in M&I and continue deforestation, albeit at a slightly lower rate; therefore, farmers shift from palm plantations to cultivation of other crops (Fig. 1).

With the restriction on oil palm in M&I, harvested area of other oil crops in this region grows by 0.9 Mha, and area in other crops grows by 1.7 Mha (Fig. 1, *Top Left*). This shows that with no economic incentives to preserve forests, when oil palm expansion is restricted, the harvested area of other crops is likely to increase in M&I, somewhat offsetting the beneficial decrease in oil palm expansion. Under *TAX*, the restriction on oil palm saves only 0.36 Mha of land from deforestation in M&I (Fig. 1, *Bottom Left*). This is in line with the findings of other recent studies (1, 5, 6) that have concluded that restricting consumption of palm oil produced in M&I will not halt deforestation in this region, because palm oil is not the sole driver of deforestation.

Under *TAX*, there are also important responses in the RoW. Indeed, imposing a restriction on production of oil palm in M&I increases the harvested area of other oil crops in the RoW by 2.4 Mha (Fig. 1, *Top Left*). This expansion reduces the harvested area of nonoil crops outside of M&I by 2.2 Mha. The restriction on oil palm produced in M&I reduces harvested area of this oil crop in the RoW by a negligible, statistically insignificant (at a 95% confidence level) area of 0.048 Mha (Fig. 1, *Top Left*; RoW oil palm). That is because, compared with the baseline, this restriction changes relative crop prices in favor of nonoil palm crops in the RoW, where oil palm is largely destined for domestic consumption. The changes in relative crop prices discourage production of oil palm in regions that produce competing oil crops for the now more valuable export market. When combined with the M&I impacts, the worldwide harvested area of oil palm drops by ∼3.1 Mha (Fig. 1, *Top Left*). In light of the fact that yields of oil palm (oil per hectare) are significantly larger than yields of other oil crops, large increases in areas of other oil crops at the global scale may be expected; however, this expectation ignores the market-mediated consumption response to higher oilseed prices. (We further discuss the magnitude of this consumption response below.) Owing to the ensuing reduction in consumption of vegetable oils, the net total change in harvested areas of soybeans, rapeseed, and other oilseeds (labeled "other oil crops" in Fig. 1) is roughly equal and opposite in size to the reduced oil palm area, ∼3 Mha (Fig. 1, *Top Left*), and worldwide total harvested area is nearly unchanged.

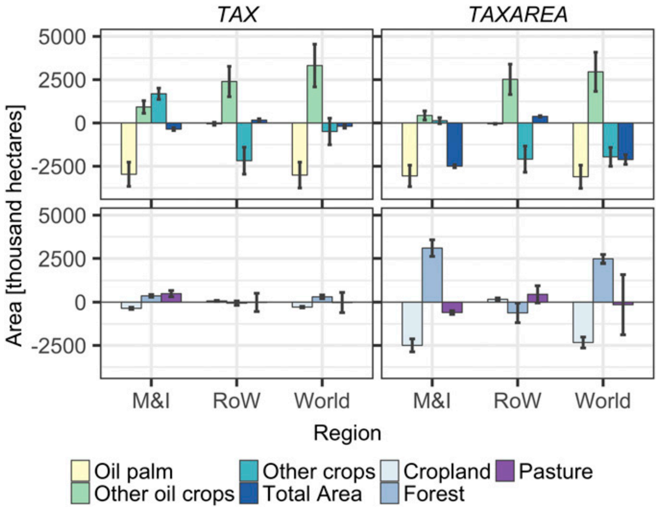

Fig. 1. Impacts of *TAX* (*Left*) and *TAXAREA* (*Right*) on crop harvested area (*Top*) and land cover (*Bottom*). Error bars represent 95% confidence intervals.

Preserving Tropical Forests Requires Direct Intervention into the Land Market. A logical policy response to the failure of *TAX* (restriction on M&I oil palm production) to significantly slow deforestation in that region is to intervene directly in the land market. Under *TAXAREA*, we introduce a forest land subsidy in addition to the production tax. In this case, the total harvested area in M&I in 2016 is 2.5 Mha below the baseline, leading to much less deforestation (Fig. 1, *Top Left*). This policy saves ∼3 Mha of deforestation in M&I, although it generates an additional 0.5 Mha of deforestation in the RoW as production expands in other regions. The result is 2.5 Mha less deforestation at the global scale (Fig. 1, *Bottom Right*).

Under *TAXAREA,* we observe only marginal increases in other crops in M&I. However, crop switching in the RoW remains significant under *TAXAREA*, since the world price effects generating this response—namely, the rise in palm oil prices—are quite similar to those in *TAX*. The land use implications of the third policy scenario, *TARIFFAREA*, in which the domestic tax on oil palm production is replaced with an international tariff on M&I palm oil consumed in the RoW, are very similar to the land use impacts of *TAXAREA*, since the targeted reduction in production relative to baseline is the same under the 2 policies (*SI Appendix*, Table S1).

Restricting Consumption of Palm Oil Produced in M&I Reduces Terrestrial Carbon Emissions. To examine the extent to which these land use changes affect terrestrial carbon emissions, we used the land use emissions model developed by Plevin et al. (12) and adopted by the California Air Resources Board (13) to calculate induced land use emissions for biofuels. Henceforth, we refer to this model as the AEZ-EF model, as it bases its calculations on emissions factors (EF) that vary across the globe according to land cover type and agro-ecological zone (AEZ). This model takes as its input the GTAP-BIO results for land cover changes and calculates the associated terrestrial CO_2 emissions, taking into account changes in crop biomass as well. To evaluate terrestrial carbon emissions induced by palm plantations in M&I, the AEZ-EF model follows Edwards et al. (14) and assumes that one-third of oil palm plantation expansion in this region occurs on peatlands. More recent publications using improved data have provided lower rates of oil palm on peatlands for Malaysia and also Indonesia. Gunarso et al. (15) estimated 22% and 13% rates of oil palm on peatlands for Indonesia and Malaysia, respectively, in 2010. In a recent work Miettinen et al. (16) created high-resolution maps for the peatland areas of peninsular Malaysia, Sumatra, and Borneo (the major oil palm plantation areas in M&I) and concluded that 20% of these areas have been disturbed for oil palm plantations. Using these maps, Zhao (17) calculated that 19% of the expansion of oil palm in these study areas were developed on peatlands. This figure is consistent with the most recent estimates of the share of plantation expansion onto peatlands (20%) from Austin et al. (3) over the period 1995 to 2015. Thus, while the Roundtable on Sustainable Palm Oil (RSPO) bans large plantings on peatland, it has not eliminated this practice, and recent available evidence suggests no detectable avoidance of peatlands (6).

Accordingly, given the uncertainty in this critical factor, we conducted a sensitivity analysis to cover a range of values for the peatland share of expansion in oil palm. Specifically, we modified the AEZ-EF model to calculate land use emissions for 4 values—0%, 10%, 20%, and 30%—for the share of peatland in land conversion under our 2011 to 2016 baseline and counterfactual experiments.

The domestic production tax in M&I (*TAX*) generates the smallest savings in land use emissions, from a negative savings of −83 MMT of CO_2 equivalent for 0% palm on peat to 2,667 MMT of CO_2 equivalent for 30% palm on peat (Fig. 2). (The negative carbon savings with 0% palm on peat arises because it only saves 0.36 Mha of land from deforestation in M&I but transfers high-biomass oil palm trees to low-biomass crops, such as soybeans.[2]) Avoiding palm plantation expansion on peat land generates much larger land use emissions savings.

When the production tax restriction on oil palm is supported with the forest subsidy (*TAXAREA*), the savings in land use emissions are much larger, ranging from 2,013 MMT of CO_2 equivalent for 0% palm on peat to 4,925 MMT of CO_2 equivalent for 30% palm on peat. The global greenhouse gas (GHG) emissions from land use and land use changes were at least about 4,500 MMT of CO_2 equivalent per year over 2000 to 2010 (18). Based on observed annual land use emissions for 2011 to 2016, the *TAXAREA* policy could have saved between 9% and 22% of the global land use emissions over this period, depending on the share of oil palm expansion on peat land. These values indicate that coupling the restriction on oil palm production with measures to control deforestation is critically important. The land use emissions savings for *TARIFFAREA* are very similar to the estimates for *TAXAREA* (Fig. 2).

Asia, Particularly China, Will Pay Higher Prices for Vegetable Oils under the Policy Scenarios. In general, the Consumer Price Index of vegetable oils rises worldwide under all 3 policies, with the exception of domestic M&I prices under the *TARIFFAREA* scenario (Fig. 3, *Top*). The *TARIFFAREA* policy generates the largest vegetable oil price increase outside of M&I, with the Food Price Index in China, where palm oil imports are very high and compose a relatively large share of consumption, rising by 7%. The Food Price Index rises by roughly 3% in the major oilseed-producing regions, including the United States, Brazil and South America, and the European Union. Within the M&I region, the first 2 policies, aimed at reducing consumption of palm oil produced in M&I through a domestic tax on oil palm in this region, increase the price index of vegetable oils in this region by 5% to 7.5%. However, the third policy, which restricts the consumption of palm oil using a global tariff on palm oil produced in M&I, depresses the price index of vegetable oils in this region as the demand for M&I palm oil in the RoW declines.

Reduced Consumption of Palm Oil Produced in M&I Can Significantly Alter Real Wages in This Region. The 3 policies affect the real wage rate mainly in M&I and regions that are major importers of palm oil (e.g., China), as shown in Fig. 3, *Bottom*. *TAX* results in an increase in real wages in M&I compared with baseline. Given its monopoly power in world markets, the domestic restriction of palm oil sales raises export prices relative to import prices, thereby contributing to an improvement in the M&I region's terms of trade. This macroeconomic improvement transfers to the household level in the form of higher real wages. However, under the *TAXAREA* policy, in which cropland area expansion is limited, the reduced demand for labor overwhelms the terms of trade effect, leading to a real wage decline in M&I. These changes in real wage for M&I are statistically significant at the 95% confidence level for *TAX* and *TAXAREA* (Fig. 3, *Bottom*). For *TARIFFAREA*, where the terms of trade for M&I deteriorate as a consequence of the diminished foreign demand for palm oil exports, the real wage drops as well; however, this change is not statistically significant (Fig. 3, *Bottom*).

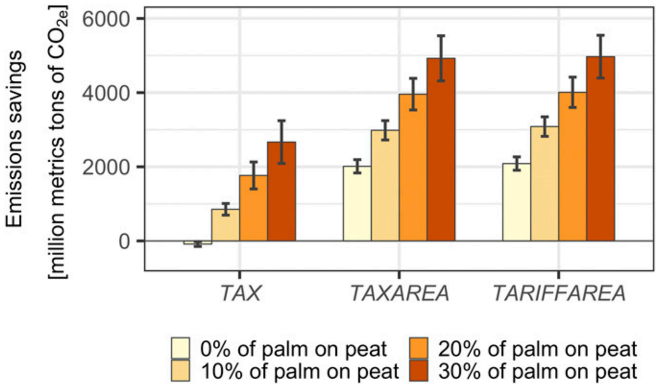

Fig. 2. Savings in land use emissions due to restrictions on palm oil expansion under the 3 alternative policies. Error bars represent 95% confidence intervals.

By limiting agricultural activity, the 3 policies result in a shifting of labor from agricultural to nonagricultural activities in M&I. Under the *TAX* policy, the employment of unskilled labor in agricultural activities drops by 1.4% in this region. The *TAXAREA* policy results in stronger shifts in labor demand, as this policy further restricts agricultural activities. Under this policy, employment of unskilled labor in agricultural activities drops by 4.5%. The shifts in employment under *TARIFFAREA* are very similar to those under *TAXAREA*.

Global Consumption of Vegetable Oils and Fats Is Reduced. In general, the 3 examined policies serve to reduce consumption of vegetable oils and fats at the global scale (*SI Appendix*, Fig. S10, *Top*). Compared with baseline, the global consumption of these products falls by 7.5 MMT under *TAX*, by 8.1 MMT under *TAXAREA*, and by 8.3 MMT under *TARIFFAREA*. These reductions in the global consumption of oils and fats range from 3.6% to 3.9% in 2016. The main reduction occurs in the consumption of oils and fats used in food and other products, including cosmetic products (*SI Appendix*, Fig. S10, *Top*). Consumption of oils and fats used in biodiesel production also drops.

A Restriction on Palm Oil Increases Production of Other Vegetable Oils and Fats. With a restriction on the market for palm oil, supplies of nonpalm sources of oils and fats increases compared with baseline (*SI Appendix*, Fig. S10). Increases in the supplies of soybean oil and rapeseed oil are <1 MMT under the 3 policy scenarios, but supplies of other vegetable oils (including coconut oil) and fats increase by >1.5 MMT.

Importers of Vegetable Oils and Oilseeds Bear the Costs of Limiting Consumption of Palm Oil Produced in M&I. This restriction affects the prices of many goods and services, alters wage rates and returns to agricultural land, and affects economy-wide gross domestic product. The GTAP-BIO model calculates the monetary values of

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[2] The EF-AEZ model calculates emissions from changes in land cover and emissions due to changes in crop biomass. The figures reported herein include the sum of these 2 items. For *TAX* with 0% palm on peat, the saving in emissions due to preserving forest is positive but small compared with the loss in biomass of oil palm trees vs. the biomass of other crops.

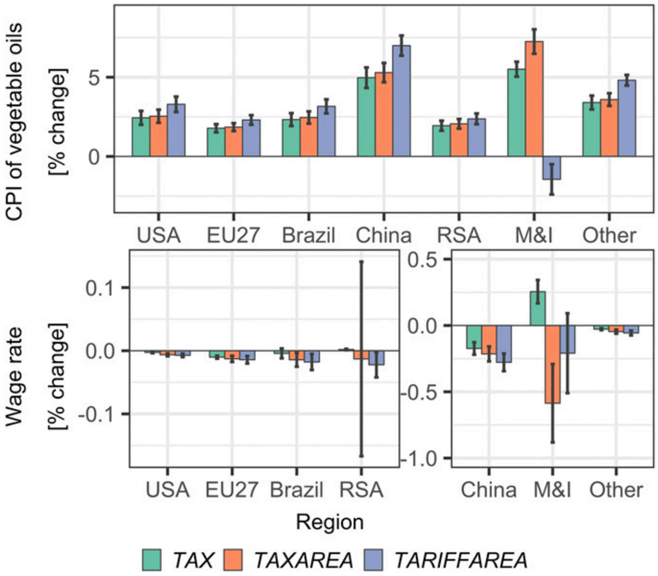

Fig. 3. Changes in the Consumer Price Index of vegetable oils (*Top*) and real wage rate (*Bottom*) due to restrictions on palm oil expansion under the 3 alternative policies. Error bars represent 95% confidence intervals. RSA, rest of South America.

these changes by region and computes the associated changes in welfare, expressed as a percentage of initial spending in each region. However, this market-based measure of welfare does not account for the social benefits associated with reduced GHG emissions. Therefore, we would expect the global change in monetary welfare reported here to be negative. We focus primarily on the regional distribution of these market-based welfare impacts.

The 3 policy interventions reduce market-based global welfare by $4,300 million for *TAX*, by $5,532 million for *TAXAREA*, and by $7,398 million for *TARIFFAREA*. This represents the cost of mitigating GHG emissions via this channel (ignoring the benefits). The major oil crop producers/exporters, including the United States, Brazil, and the rest of South America, gain market welfare under all 3 policies, ranging from $400 million to $1,100 million (Fig. 4, *Top*). These regions produce more oilseeds at higher prices. On the other hand, China and the other oilseed-importing regions (representing the RoW) lose market-based welfare (Fig. 4), consuming less oilseeds and vegetable oils at higher prices. Market-based welfare in the European Union, which produces large quantities of oil crops and oilseeds and imports large quantities of palm oil, drops.

M&I, the world's largest and main palm oil-producing region, gains $1,867 million under *TAX*, which freezes the supply of oil palm from this region over the 2011 to 2016 period using a production tax. This increases the price of palm oil at the global scale compared with baseline, which raises export prices and improves the region's terms of trade. The production tax also generates an efficiency cost, but this is smaller than gains in terms of trade (*SI Appendix*, Table S2). Under *TAXAREA*, when the forest subsidy to control deforestation is added, the production tax in combination with the subsidy generates greater market-based efficiency costs to the economy and thus leads to smaller overall welfare gains ($1,053 million) compared with *TAX*, a result consistent with the literature on this topic (19).

Finally, the third policy, *TARIFFAREA,* which replaces the domestic production tax on oil palm with a global tariff on palm oil imported from M&I, leads to a very different regional welfare distribution. It generates a sizeable loss of market welfare ($4,693 million) in M&I, stemming from the reduced demand, and hence diminished prices, for the region's palm oil exports, leading to major losses in terms of trade (*SI Appendix,* Table S2). Therefore, among the examined policies, this is the worst outcome for M&I, based on this market-based welfare criterion. It is also the costliest policy at the global scale. However, one region's terms of trade loss is another region's gain, and the *TARIFFAREA* policy generates gains for the United States of America, Brazil, and the rest of South America, which are the main producers of competing oilseeds. In summary, from a market welfare standpoint, the M&I region benefits when it takes the initiative to reduce global consumption of palm oil, but loses market welfare when other regions implement the policy.

Targeting Deforestation Directly Is Required for a Cost-Effective Policy Package. A useful summary metric compares the market-based cost of limiting GHG emissions (i.e., global market welfare impacts) per unit emissions saved, which is commonly expressed as dollars per metric ton of savings in $\mathrm{CO_2}$ emissions equivalent (\$/MT $\mathrm{CO_2e}$). According to this metric, *TAX* is the most expensive policy and *TAXAREA* is the cheapest, regardless of the share of palm expansion on peatland (Fig. 4, *Bottom*). *TARIFFAREA* falls between the other 2 policies in terms of \$/MtCO2e mitigated. As noted above, the *TAX* policy generates no savings in emissions with a 0% share of palm on peatland. For this policy, the cost of emission savings is ~5 \$/MT $\mathrm{CO_2e}$ with a 10% share for palm on peat. The cost of *TAX* policy for 30% palm on peat is 1.62 \$/MT $\mathrm{CO_2e}$. The corresponding figures for *TAXAREA*, the cheapest—and thus most economically efficient—policy, are 1.85 \$/MT $\mathrm{CO_2e}$ and 1.12 \$/MT $\mathrm{CO_2e}$, respectively. All these policies appear to be socially beneficial compared with current estimates of the social cost of carbon, which range from \$11 to \$105 for the $\mathrm{CO_2}$ emitted in 2015 according to recent estimates (20).

Discussion and Limitations

The results obtained from the experiments examined in this paper indicate that limiting total output (and hence consumption) of palm oil produced in M&I is expected to reduce deforestation rates in that region. However, this restriction does not halt deforestation in M&I, as oil palm is not the sole crop being produced. A restriction on the consumption of palm oil produced in M&I supported by an initiative that directly limits deforestation is

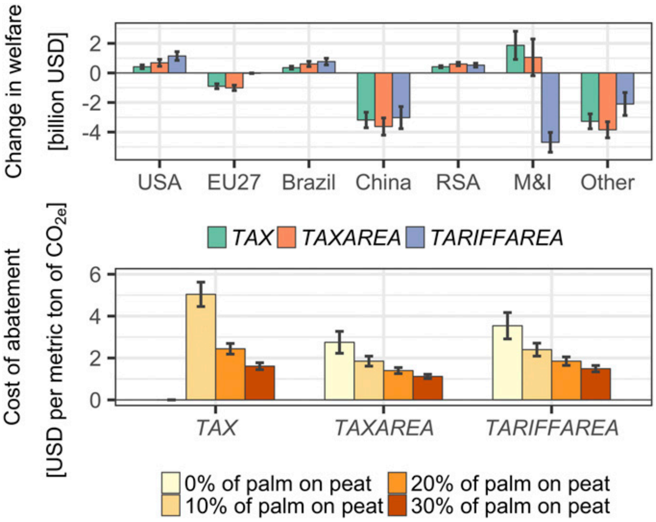

Fig. 4. Changes in market-based welfare (*Top*) and cost per metric ton of terrestrial carbon emissions abated (*Bottom*) due to restrictions on palm oil expansion under alternative polices. Error bars represent 95% confidence intervals. RSA, Rest of South America. (*TAX* provides no savings in emissions for 0% of palm on peatland.)

needed to prevent additional deforestation, carbon emissions, and biodiversity loss. Targeting just a single driver of deforestation in M&I opens room for other drivers of deforestation to operate more actively in the absence of a forest protection plan. This echoes arguments in the "land-sparing" literature noting that active conservation efforts need to be coupled with agricultural innovation to overcome rebound effects (21).

Such complex responses to targeting policies have also been recognized in the land system science literature (22, 23), encompassed in market-mediated responses, including leakage (whereby a land use restriction in one location shifts the activity elsewhere), rebound (whereby the price-lowering effect of efficiency improvements leads to increased consumption), and indirect land use change (whereby land use change in one location leads to a land use change elsewhere). In our experiments, all 3 processes are at play and interact with one another through this global general equilibrium framework. Restriction of oil palm expansion in M&I does lead to leakage, as well as to the expansion of other oil crops in the RoW. Furthermore, the palm oil restriction policies lead to an increase in the price of oilseeds and a decrease in the overall consumption of vegetable oils. Our results also capture the indirect land use changes in the RoW resulting from an intervention in the M&I.

An international regulation that limits consumption of palm oil produced in M&I using a restriction on trade of this product (e.g., imposing a tariff on palm oil imported from M&I) would be far more costly for the M&I region compared with effective domestic regulations. In short, M&I will be better off undertaking their own regulations as opposed to leaving it to other regions to undertake import-limiting policies. By restricting output and forest land conversion domestically, the M&I region can reap the benefits of higher palm oil prices. When they leave it to others to implement import restrictions, these benefits go to the importers in the form of higher tariff revenues and increased export prices. One might logically ask that if this output tax is so beneficial to the M&I region, why have they not previously exploited this market power? The answer lies in the intranational distributional consequences of this policy. While it benefits the country as a whole, it does so by depressing returns in the palm oil sector. Only when the sector is nationally owned—as is the case with much of the world's crude oil production—might we expect to see such an exercise of monopoly power in production.

Imposing a restriction on palm oil shifts demand toward other types of vegetable oils and fats; however, the replacement is not one-for-one since the restriction reduces overall consumption of vegetable oils. The restriction also has a significant impact on real unskilled wages in M&I and elsewhere in Asia, as agriculture remains a significant employer of unskilled workers, and vegetable oil is a key consumption item for many households.

Our analysis highlights the role of markets in determining the medium-run economic impacts of a restriction on palm oil and reflects the market-mediated land use change induced by this restriction. Given the focus on market mechanisms, our analysis might not capture the role of some key institutions (e.g., laws, rules, and traditions that govern land use). Of course, over time, these institutions may themselves be sensitive to market forces.

It is also important to emphasize that the modeling framework used in this paper does not capture potential long-run responses to these policies. Our analysis takes into account switching among existing oil crops, expansion in palm oil in non-M&I regions where it is already produced at a commercial level, and substitution of vegetable oils in response to higher palm oil prices due to restrictions on palm oil production in M&I. However, these are all medium-run implications of palm oil restrictions. In the longer run, higher worldwide palm oil prices may encourage the production of palm oil in entirely new areas of South America and Africa. In addition, over the very long run, entirely new oil crops with limited land use implications (e.g., *Brassica carinata*) may come to dominate global markets. These long-run responses to restrictions on oil palm production in M&I will clearly alter our findings, potentially generating even greater savings in terrestrial carbon, forests, and biodiversity.

Finally, the policies examined here rely heavily on economic incentives to limit production of palm oil and control deforestation. In practice, it may not be easy to effectively define and implement these polices due to governance challenges, including corruption, and conflicts of interest among the stakeholders and countries involved in this process (24, 25).

Materials and Methods

Taheripour et al. (26) described the latest version of GTAP-BIO. This model traces production, consumption, and trade of all goods and services at the global scale. Unlike the standard model, GTAP-BIO disaggregates oil crops, vegetable oils, and meals into several categories, including soybean, rapeseed, oil palm, other oil seeds, soy oil, rapeseed oil, palm oil, other oils and fats, soy meal, rapeseed meal, palm kernel meal, and other meals. In addition, GTAP-BIO represents production and consumption of biofuels and their by-products and traces land use across the world at the AEZ level. It handles intensification in crop production and uses a benchmark database that represents the global economy in 2011. Its parameters were tuned to recent observations of global land use and land cover change (*SI Appendix*, section 5).

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