## Supplementary Material for Food security under high bioenergy demand toward long-term climate goals


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# Supplementary Text

## Supplementary Text 1: Methods to estimate the population at risk of hunger

The population at risk of hunger is calculated outside the models by using the FAO approach.(FAO, 2008) Amounts of food consumption vary among households within a country, and people who eat less than the minimum energy requirement face the risk of hunger. The models calculate mean per-capita food consumption for a representative household. The proportion of the population at risk of hunger is estimated from the mean per-capita food consumption, the minimum energy requirement, and the coefficient of variation of distribution of dietary energy consumption among households within each country.(FAO, 2008) Future changes in inequality of food distribution in a country are considered by changing the coefficient of variation along with income growth. We assumed no risk of hunger for high-income countries. (See earlier studies for more details on the methods used to estimate the risk of hunger.)

$$Risk_t = POP_t \cdot PoU_t \qquad \text{(Eq. 1)}$$

where,

t: year

*Riskt*: population at risk of hunger in year *t* [person]

*PoPt*: population in year *t* [person]

*PoUt*: prevalence of undernourishment in year *t* [-]

According to the Food and Agriculture Organization (FAO) methodology, the proportion of the population at risk of hunger is defined using Eqs. 2 to 4. With the FAO methodology, the proportion is calculated using three parameters: the mean food calorie consumption per person per day (*cal*), the mean minimum dietary energy requirement (*M*), and the coefficient of variation of the food distribution of the dietary energy consumption in a country (*CV*). The food distribution within a country is assumed to obey a standard normal cumulative distribution. The proportion of the population under the mean minimum dietary energy requirement (*M*) is defined as the proportion of the population at risk of hunger. The standard normal cumulative distribution has two parameters, the mean $\mu_t$ and the variance $\sigma_t$, as in Eq. 2. The parameters $\mu_{t,}$ and $\sigma_t$ can be represented using the mean food calorie consumption per person per day (*cal*) and the coefficient of variation of the domestic distribution of dietary energy consumption (*CV*) as Eqs. 3 and 4.

$$PoU_t = \Phi\left( {\log M_t - \mu(cal_t, \sigma_t)} \middle/ {\sigma_t} \right) \quad \text{(Eq. 2)}$$

$$\mu(cal_t, \sigma_t) = \log_e cal_t - {\sigma_t^2}/{2} \quad \text{(Eq. 3)}$$

$$\sigma_t = \left[\log_e\left(CV^2 + 1\right)\right]^{0.5} \quad \text{(Eq. 4)}$$

*where,*

$M_t$ : mean minimum dietary energy requirement in year $t$

$CV_t$ :coefficient of variation of the inter-national distribution of dietary energy consumption in year $t$

$\Phi$ : standard normal cumulative distribution

$cal_t$ :mean food calorie intake per person per day in year $t$

## Supplementary Text 2: Effects of bioenergy feedstocks on food security

To explore possibility of a better combination of bioenergy feedstock for food security, we performed a sensitivity analysis using a set of scenarios where 200EJ of global modern bioenergy demand is supplied by different bioenergy feedstock; i) energy crops, ii) woody energy crops, iii) crop residues, and iv) managed forest.

If bioenergy is produced only by energy crops or woody energy crops, then cropland for energy needs to expand to supply the same amount of energy. For example, to meet demand of 200EJ only by bio-crops, additional 200-300Mha cropland is needed compared to the case the demand is supplied by mixed feedstock. This additional land demand strengthens land conflict and put more pressure on agricultural land. The direction of change in land varies across models as same as shown above in the case where bioenergy demand increases. If only cropland with low productivity is replaced by bio crops and land with high yield is remained for food, then cropland for food become smaller. But if cropland with high yield is used for energy, then cropland need to expand to meet food demand. These competitive land increases food price and then lead food insecurity and more hunger. On the other hand, if bioenergy demand is supplied only from crop residue (R) and managed forest (F), no land is needed for bioenergy production and then cropland area for food is kept and decrease food price then increase food consumption and reduce undernourishment. Relying on bioenergy only from bio crops increases the impact on food. On the other hand, the influence on food can be relaxed by combining energy derived from residue and managed forest.

## Supplementary Text 3: Effects of land protection and taxing on forest carbon stock on food security

To explore the possibility of a better combination of land-based mitigation options and their effect on food security, we performed a sensitivity analysis using a set of scenarios with different levels of land protection and afforestation. All the model used the common data set for the protected area (FRA, 2010) though the models represent it in their own way where emissions from land do is not necessarily minimized and forest with high carbon density is not necessarily protected. How to put it as constraints, and land-use categories and carbon density of protected area can be different across models.

Combination of bioenergy with other land-based mitigation options changed the levels of mitigation impact on food security. However, the levels and direction of the effects significantly vary across models. In some models (e.g. GLOBIOM and MAgPIE), the land protection and afforestation cause negligible change in land compared to that caused by bioenergy demand of 100EJ (in Figure1), and do not much affect food security. In these models, land for food is allocated non-protected area even without setting protected area. Also, forest plantation is conducted in the non-agricultural area. That is why these options do not affect food supply. In contrast, in other models (e.g. GCAM), these land-based mitigation options affect land use as well as food price and then consumption with quite opposite direction. For example, in GCAM, land protection increases pasture because unmanaged pasture is protected, but it decreases cropland since land with a high yield which is supposed to be used for crops is protected and become unavailable for food. In AIM and GCAM where afforestation is planted in agricultural land, excluding afforestation from mitigation options remain more agricultural land which is used for energy crops in AIM and for food and energy in GCAM. Implementing afforestation increases cropland needed to meet food demand but decreases pasture.

Our analysis also suggests that land protection and afforestation would bring pressure to land and leads to increases in food prices and the population at risk of hunger unless area and location of protection and afforestation are not carefully selected. The degree of influence depends on which land is protected and planted. That is, protection of existing forests does not affect food, but if highly productive lands suitable for agriculture are protected, the broader agricultural land is needed to meet food needs. Likewise, afforestation raises the pressure when it is applied to agricultural land.

We assumed the present forest conservation area (FRA, 2010), but this is just one assumption. Since this target of protection is mostly existing forest, this assumption did not affect food. It is necessary to careful discussions with regional policy makers and stakeholders in judging future protected areas. The land to be protected may need to cover not only the existing forest but also various land segments from the viewpoint of biodiversity and ecosystem value.

On the other hand, the afforested area depends on the forest growth rate, a set of mitigation options and its mitigation potential, assumed by each model. The models where mitigation relies heavily on afforestation has a strong impact on food systems through afforestation. If there is a buffer by having abundant mitigation technologies such as improvement technology of agricultural mitigation technology, improvement of forest and production system management in addition to emissions reduction technologies at the energy sector, the influence on afforestation by food is suppressed. In this scenario framework, feedback to the carbon budget of carbon absorption by afforestation is not considered. It is not taken into account that the increase in afforestation will reduce bioenergy demand. For this point, further research is necessary with a consistent framework.


Figure S 1 Observed relation between income and equality of food domestic distribution (FAO, 2013) and future estimated changes in equity of food distribution (Hasegawa et al., 2015a; Hasegawa et al., 2015b).

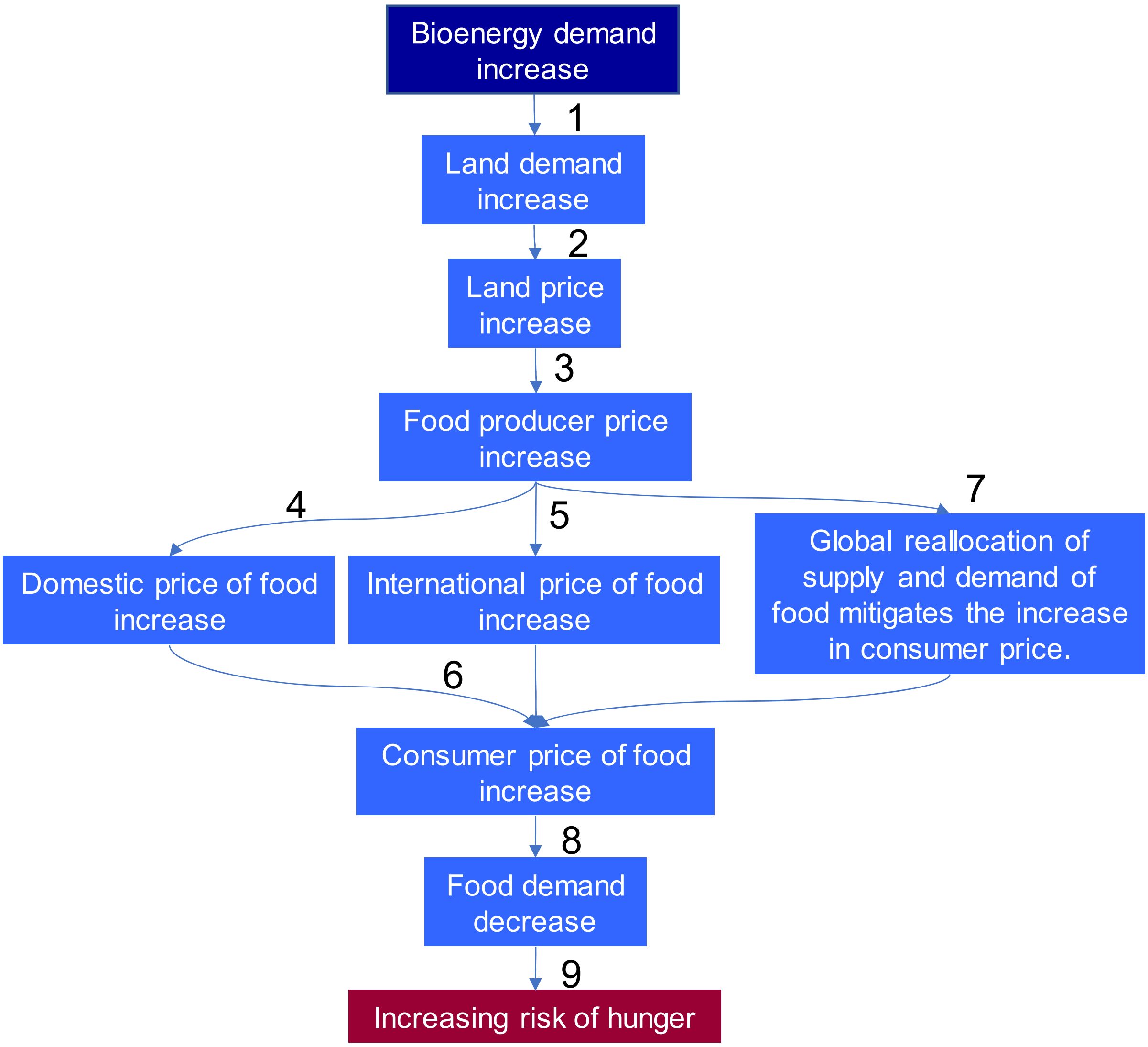


**Figure S 2** A flow of price transmission from bioenergy implementation to the risk of hunger

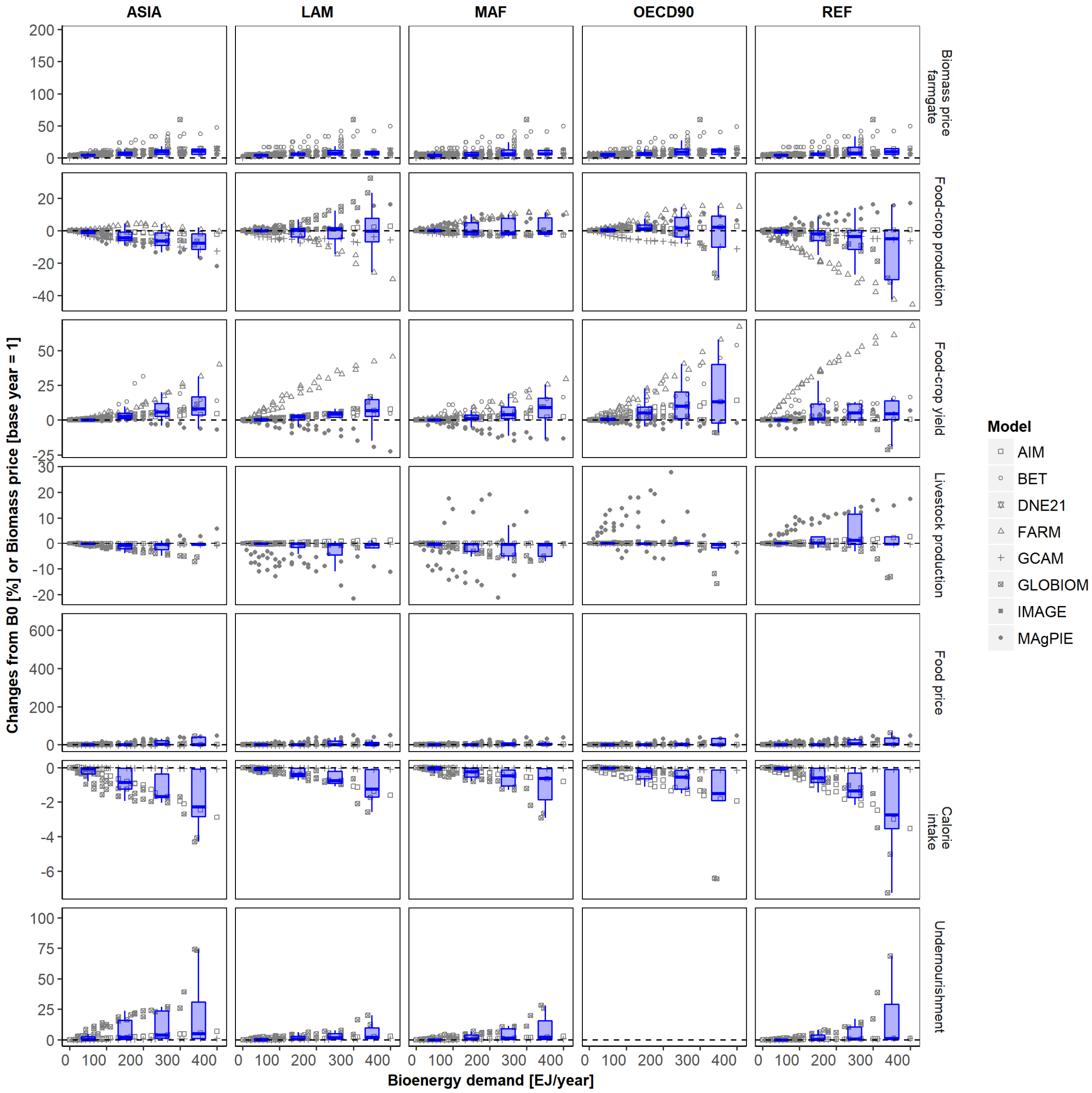


Figure S 3 Regional food security indicators responding to the different levels of global modern bioenergy demand. Values represent percentage change from the level of no bioenergy demand (B0). Bars show 90% confidential range for each model. Boxes and whiskers show the uncertainty range across the models. Boxes represent the 1st-3rd quartile range and the plain line indicates the median

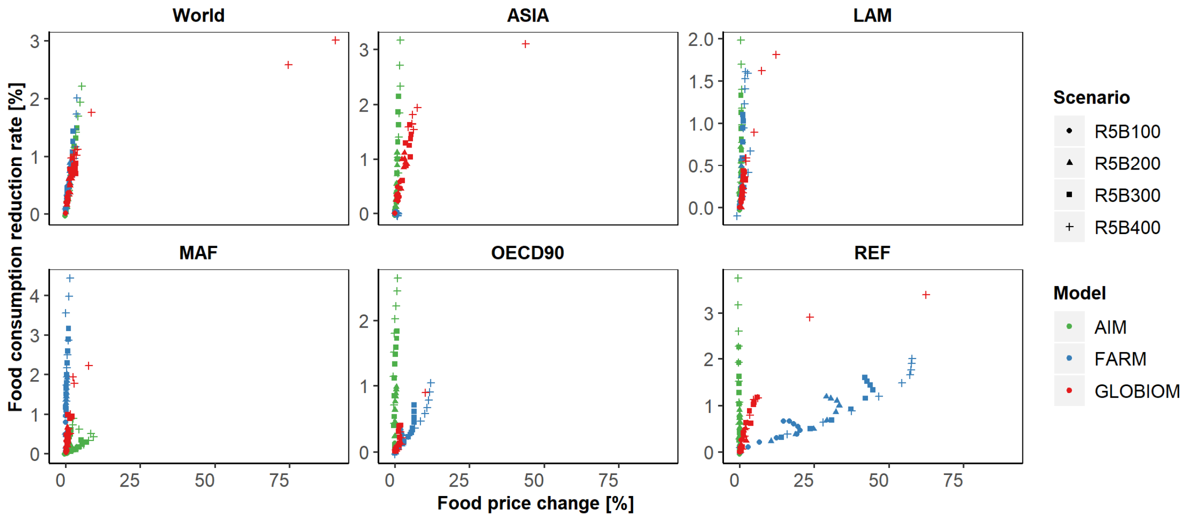


Figure S 4 Agricultural prices and reduction in food consumption show different relationships among regions and scenarios with different amounts of bioenergy demand. Regional codes are OECD90: OECD regions, Asia: Asia, REF: Reforming economies(Eastern Europe and part of former Soviet Union), MAF: Middle East and Africa, and LAM: Latin America.

Table S 1 Representation of the price transmission in models

| | AIM/CGE | FARM | GCAM | GLOBIOM | MAgPIE | NLU |
|---|---|---|---|---|---|---|
| 1. Bioenergy demand increases land demand. | X | X | X | X | X | X |
| 2. Land demand increases land price. | X | X | X | X | X | X |
| 3. Increase in land price increases food producer price. | X | X | X | X | X | X |
| 4. Increase in food producer price increases domestic food price. | X | X | X | X | X | X |
| 5. Increase in food producer price increases international food price. | X | X | X | X | X | X |
| 6. Increase in domestic and international food prices increases food consumer price. | X | X | X | X | X | X |
| 7. Global reallocation of supply and demand of food through trade mitigates the increase in consumer prices. | X | X | X | X | X | X |
| 8. Increases in food consumer price decrease food demand. | X | X | X | X | | X |
| 9. Decrease in food demand increases risk of hunger. | X | X | X | X | | X |

Table S 2 Overview and description of bioenergy and agricultural modeling approaches in models

| Model | | AIM | FARM3.1 | GCAM | GLOBIOM | MAgPIE | NLU 1.0 |
|---|---|---|---|---|---|---|---|
| Model type | | CGE | CGE | PE | PE | PE | PE |
| Agricultural market mechanism | Supply | Profit maximization | Profit maximization | Economic competition for land to produce crops and forest products. | Market equilibrium | Cost minimization | Cost Minimization |
| | Demand | Cost minimization | Cost minimization | Per capita Demand for food crops is inelastic, demand for meat is income and price elastic | Market equilibrium | Exogenous demand scenario (unresponsive to price changes) | Exogenous demand scenario (unresponsive to price changes) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Agricultural commodities (resolution) | Non-Energy (Food) crops | 7 groups | 7 types | 12 groups | 18 crops | 16 types | 11 crops aggregated into one representative crop. The dynamic of the other crop types is exogenously set based on FAO projection (Alexandratos and Bruinsma, 2012) |
| | Energy crops | 1 groups | 1 type | 2 groups | Short rotation plantation | 2 types | 2 types |
| | Livestock products | 3 groups | 3 types | 5 groups | 6 livestock products (meat, milk, eggs) | 5 types | 3 types |
| | Other | No | 1 (plant-based fibers) | fiber crops | - | No | Agricultural and forestry residues |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Forest commodities (resolution) | Wood | 1 group | 1 type | 1 group | 6 different final products for material use and intermediate products, fuelwood, residues etc. for traditional and modern energy use | No | 1 type |
| | Other | No | Forest residues | residues for energy | - | No | |
| Land market mechanism | Supply (biophysical) | Profit maximization | Profit maximization | Profit maximization as modeled by economic equilibrium | Market equilibrium | Cost minimization | Cost minimization |
| | Demand (economic) | Cost minimization | Cost minimization | Profit maximization | Market equilibrium | Cost minimization | Exogenous |
| Land use types | Cropland | Dynamic | Dynamic | Dynamic | Dynamic | Dynamic | Dynamic |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Bioenergy Cropland | Dynamic | Dynamic | Dynamic | Dynamic | Dynamic | Dynamic |
| | Pasture | Dynamic | Dynamic | Dynamic | Dynamic | Dynamic | Dynamic |
| | Forest | Dynamic | | Dynamic | Dynamic | Dynamic | Exogenous |
| | Managed Forest | Dynamic | Dynamic | Dynamic | Dynamic | Constant | Dynamic |
| | Urban | Constant | | Constant | Constant | Constant | Constant |
| | Other Land | Dynamic | | Dynamic | Dynamic | Dynamic | Constant |
| Interactions with agricultural market | Energy | Energy as intermediate input to agricultural production, Bioenergy production from agricultural sector | Energy as intermediate input to agricultural production; Bioenergy production from agricultural sector | Bioenergy demand | Bioenergy demand | Bioenergy demand | Bioenergy demand Fertilizer price |
| | Economy | labor, capital markets | Labor, capital markets | Bioenergy prices and Carbon prices | Bioenergy prices and carbon prices | Bioenergy prices and GHG prices | Bioenergy prices and Carbon prices |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Climate/policy | Carbon prices, GHG emissions | Carbon price, $CO_2$ emissions | GHG emissions | GHG emission | GHG emissions | GHG emissions |
| Temporal resolution | | 1 year step | | 5 year time steps to 2100 | 10 year time steps up to 2100 | 5 year time steps to 2100 | |
| Spatial resolution | biophysical | 0.5 × 0.5 degree grids | Up to 18 AEZs per world region | 283 world regions | 0.5 x 0.5 degree grids | 0.5 × 0.5 degree grids | 60 land classes per region |
| | economy | 17 world regions | 15 world regions | 32 world regions | 30 world regions | 10 world regions | 12 world regions |
| Crop yields | Technological change | Exogenous | Exogenous | Exogenous | Exogenous | Partly endogenous in EMF33 supply study (endogenous TC from R5B0 scenario is used as exogenous input in all other scenarios) | Endogenous for annual crop yield, exogenous for perennial crop yield. |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Irrigation | Yes | Implicit within each AEZ | Not explicit in GCAM version used here | Yes | Yes | Yes |
| | Irrigation dynamics (efficiency increase, irrigation expansion) | Yes | No | No | Yes | Yes | No |
| | Management change | No | Implicit in production function | no | Yes | Yes | Yes |
| GHG emissions | Energy [CO2] | Yes | Yes | yes | - | Yes, in combination with REMIND | Yes |
| | Land Use Change [CO2] | Yes | Yes | Yes | Yes | Yes | Yes |
| | Livestock [CH4, N2O] | Yes | No | Yes | Yes | Yes | Yes |
| | Cropland [CH4, N2O] | Yes | No | Yes | Yes | Yes | Yes |
| | Afforestation | Yes | Yes | Yes | Yes | Yes | No |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| LU mitigation options | Reforestation | Yes | Yes | Yes | Yes | Yes | No |
| | Forest management | No | Implicit in production function | No | Yes | No | No |
| | Avoided deforestation | Yes | No | Yes | Yes | Yes | No |
| | Bioenergy | Yes | Yes | Waste, residues, 1st and 2nd generation bioenergy crops | Residues, forest biomass, 1st (kept constant for EMF33) and 2nd generation bioenergy crops | Residues, 2nd generation bioenergy crops | Yes |
| | Agricultural Management [CH4, N2O] | Yes, as an aggregated form as agricultural mitigation measures | No | Yes | Yes | Yes | Yes |
| | Agricultural soil carbon management [CO2] | Yes, as an aggregated form as agricultural mitigation measures | No | No | No | No | Yes |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | BECCS | Yes | Yes | yes | - | Yes, in combination with REMIND | |
| | Other | No | | | - | No | |
| Reference | | Fujimori et al. (2012), Hasegawa et al. (2017) | Sands et al. (2017) | WISE et al. (2014) | (Frank et al., 2017; Havlík et al., 2014) | Popp et al. (2014), Popp et al. (2014) | (Souty et al., 2012); (Brunelle et al., 2015) |

1) PE; Partial Equilibrium model, CGE; Computable General Equilibrium model.

2) * Items marked by asterisk are generally available but were not activated for this particular study.

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