Induced land use emissions due to first and second generation biofuels and uncertainty in land use emissions factors

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Abstract

Much research has provided estimates of induced land use change and emissions for first generation biofuels. Relatively little has estimated land use change for the second generation cellulosic biofuels. In this paper we estimate induced land use change and emissions for these biofuels. Estimated emissions due to land use changes induced by biofuels production are uncertain not only because their associated land use changes are uncertain, but also because of uncertainty in the land use emissions factors (EFs). This paper also examines uncertainties related to these EFs and their assumptions. Three emissions factors including EFs obtained based on Woods Hole (WH) data, EFs developed by California Air Resources Board (CARB),[1] and EFs obtained from the Terrestrial Ecosystem Model (TEM) are examined. Using these three EFs, induced land use emissions are calculated for several biofuel pathways under alternative assumptions. The land use change results suggest that corn stover (and by implication other crop residues) have no significant induced land use change associated with biofuel production, but that is not the case for dedicated energy crops. Use of dedicated energy crops induces land use change and transfers natural land (in particular forest) to crop production. Producing bio-gasoline from miscanthus generates the lowest land requirement across all alterative pathways. The largest land requirement is associated with the switchgrass. The difference is due largely to the assumed yields of switchgrass and miscanthus in this analysis. The two major conclusions from this emissions analysis are: 1) inclusion or exclusion of cropland pasture makes a huge

[1] The authors are solely responsible for the contents of this paper. Neither the land use change estimates nor the emission factors used in this research have been approved by CARB.

difference; and 2) there is wide divergence among the emission factor sources, especially for dedicated crop conversion to ethanol. Inclusion of cropland pasture emissions doubles or triples the emissions obtained using the WH EFs. The estimated induced land use emissions for ethanol and bio-gasoline produced from dedicated crops are essentially the same using the WH EFs, but vastly different using the CARB or TEM EFs factors, with cellulosic ethanol producing substantially more emissions.

1. Introduction

The land use consequences of global biofuel programs and their contributions to GHG emissions have been the focal point of many debates and research studies in recent years. Research studies in this field usually estimate induced land use emissions in two phases. They first estimate induced land use changes (LUCs) due to biofuel production using either partial or general equilibrium models. Then they apply land use *emission factors* (EFs), which measure vegetation and soil carbon fluxes and are obtained from biophysical models, to calculate the induced land use emissions given the estimated LUC. Both of these phases are subject to uncertainties. Several papers examined major uncertainties related to the estimates for induced LUCs and their geographical distributions. Wicke et al. (2012) have reviewed major studies in this area and highlighted deficiencies of economic models used to assess the induced LUCs due to biofuels and their corresponding uncertainties. However, most of these studies focused on the land use emissions due to first generation biofuels such as corn ethanol, sugarcane ethanol, and biodiesel. Only few attempts have been made to estimate these emissions for second generation biofuels which convert cellulosic materials into liquid fuels. In addition, uncertainties related to the EFs and their importance for estimates of the induced emissions due to biofuels have received little or no attention to date. This paper examines uncertainties in emission estimates for induced LUCs due to the first and second generation biofuels.

To accomplish this task we first provide a set of estimates for induced LUCs from several biofuel pathways, including the first and second generation biofuels. The estimates for induced LUCs are obtained from Taheripour, Tyner and Wang (2011: Henceforth TTW). The next section of this paper presents the estimates for induced LUC. Then we describe the approaches, data sources, and assumptions for three existing major EFs. After that, induced land use emissions for selected biofuel pathways are calculated using these three different emissions factors. Finally, uncertainties in EFs and their consequences for the estimated induced LUCs for alternative biofuel pathways are examined.

2. Induced LUCs due to selected biofuel pathways

Several papers have estimated induced LUCs for the first generations of biofuels. Wicke et al. (2012) have reviewed many of these studies. However, only few studies have examined induced LUCs due to the second generations of biofuels. In a recent work TTW have reviewed the existing estimates for these biofuel and then provided a set of new estimates for induced LUCs for several biofuel pathways including corn ethanol and biofuels produced from corn stover and dedicated crops such as switchgrass and miscanthus. These authors have obtained their land use estimates using an economy-wide computational general equilibrium (CGE) model based on the modeling framework developed at Purdue University's Center for Global Trade Analysis Project (GTAP).

The model developed by these authors is an improved version of the GTAP-BIO model introduced in Tyner et al. (2010). The flowing list outlines the major modification in the GTAP-BIO model made by these authors:

- The new model uses the 2004 version 7 of GTAP data base,
- The first generation of biofuels and their by-products are introduced in the new data base,
- Six new biofuel pathways including ethanol and bio-gasoline (a drop-in-fuel) produced from corn stover, miscanthus, and switchgrass are introduced into the model,
- New industries are included into the model to produce and or collect cellulosic materials such as corn stover, miscanthus, and switchgrass and deliver them to biofuel industries,

- The land supply nesting structure is modified to handle allocation of cropland and pasture land among the traditional crops and the new energy crops,
- Based on recent evidence a greater flexibility in acreage switching among different crops in response to price changes is introduced into the model,
- An endogenous yield adjustment process is introduced into the model to account for yield improvement in cropland pasture areas,

In this model the stover industry collects corn stover and ships its output (collected corn stover) to the stover ethanol or bio-gasoline industry. This industry uses inputs including fuel, fertilizer (to maintain productivity of croplands where nutrients in stover are removed), transportation, capital, labor, and other goods and services to collect, bail, store and ship corn stover to the stover processing industry. The miscanthus and switchgrass industries are different from the stover industry. These industries produce miscanthus or switchgrass and sell their products to the processing industries. The miscanthus and switchgrass industries compete with crop producers for cropland. The biofuel industries are independent from each other and they are designed to operate using a single feedstock, either corn, corn stover, miscanthus, or switchgrass.

Since these new industries do not operate in the real world, the most updated information available in the literature is used to define the cost structures of these industries and their production technologies. The literature has wide ranging estimates of dedicated crop yields, crop production costs, conversion technology costs, and conversion yields. With assistance from experts at Argonne and NREL, a set of reasonable and consistent assumptions are used to establish the cost structures for the industries.

To evaluate the induced LUC emissions due to biofuel production and quantify their sensitivity with respect to alternative EFs we use the estimated LUCs provided by TTW for seven biofuel pathways for the US economy:

a. An increase in corn ethanol production by 11.59 billion gallons (BG) (from its 2004 level to 15 BG),
b. An increase in production and consumption of Bio-Gasoline produced from corn stover by 6 BG, on top of 15 BG corn ethanol,
c. An increase in production and consumption of Bio-Gasoline produced from miscanthus by 4.7 BG, on top of 15 BG corn ethanol,
d. An increase in production and consumption of Bio-Gasoline produced from switchgrass by 4.7 BG, on top of 15 BG corn ethanol,
e. An increase in production and consumption of ethanol from corn stover by 9 BG, on top of 15 BG corn ethanol,
f. An increase in production and consumption of ethanol from miscanthus by 7 BG, on top of 15 BG corn ethanol,
g. An increase in production and consumption of ethanol from switchgrass by 7 BG, on top of 15 BG corn ethanol.

These experiments are defined based on the targets which are included in the Renewable Fuel Standard (RFS2). The experiment (a) is accomplished using the 2004 data base, and other experiments are obtained off of the 15 BG corn ethanol. The induced LUCs due to these biofuel pathways are shown in Table 1.

Table 1. Land use changes due to biofuel production (1000 hectares)*

		Land category	US	EU	Brazil	Others	Total
(a)	15 BG Corn Ethanol Off of 2004	Forest	-331	-80	42	144	-226
		Cropland	971	126	82	899	2,078
		Pasture	-639	-46	-123	-1,043	-1,852
		Cropland pasture	-1,169	-238	-	-	-1,407
(b)	6 BG Stover Bio-Gasoline	Forest	8	2	0	47	56
		Cropland	-13	-2	-2	-15	-32
		Pasture	5	0	2	-32	-24
		Cropland pasture	0	6	-	-	6
(c)	4.7 BG Miscanthus Bio-Gasoline	Forest	-153	-16	8	24	-137
		Cropland	106	25	15	173	319
		Pasture	47	-9	-23	-197	-183
		Cropland pasture	-3,719	-43	-	-	-3,762
(d)	4.7 BG Switchgrass Bio-Gasoline	Forest	-550	-45	20	-16	-590
		Cropland	223	65	40	447	775
		Pasture	327	-20	-60	-431	-185
		Cropland pasture	- 6,915	-113	-	-	-7,028
(e)	9 BG Stover Ethanol	Forest	19	3	0	52	74
		Cropland	-13	-4	-3	-25	-44
		Pasture	-6	1	3	-28	-30
		Cropland pasture	-9	8	-	-	-2
(f)	7 BG Miscanthus Ethanol	Forest	-221	-21	11	26	-205
		Cropland	134	32	20	222	408
		Pasture	88	-11	-31	-249	-202
		Cropland pasture	-4,590	-56	-	-	-4,646
(g)	7 BG Switchgrass Ethanol	Forest	-784	-61	28	-29	-845
		Cropland	301	89	54	610	1,054
		Pasture	483	-28	-82	-581	-208
		Cropland pasture	-8,278	-154	-	-	-8,432

*Cases (b) to (g) are in addition to case (a). Positive numbers represent expansion and negative numbers indicate reduction in each category.

This table shows that producing ethanol or bio-gasoline from corn stover will generate negligible LUCs. The targeted expansion in corn ethanol will expand global cropland by about 2 million hectares (MH) and will shift more than 1.4 MH of US and Brazil cropland pasture to crop production. This table also indicates that producing either ethanol or bio-gasoline from dedicated crops will shift a considerable amount of cropland pasture to crop production. For example, as shown the last row of this table, producing 7 BG switchgrass ethanol will shift about 8.3 MH of US cropland pasture to crop production.

Table 2 summarizes the land needed per 1000 gallons of bio-gasoline or ethanol produced from corn, miscanthus or switchgrass which cause LUCs. Three important conclusions emerge from this table. First, switchgrass needs more land than miscanthus in all cases. This conclusion derives from the assumed lower yield of switchgrass compared with miscanthus. Clearly, dedicated energy crop yield is a key factor in deriving the LUCs associated with these feedstocks. Second, ethanol requires more land in all cases than bio-gasoline (in ethanol equivalents) because the conversion efficiency is assumed to be higher for the thermochemical process to produce bio-gasoline than for the ethanol bio-chemical process.

Table 2. Cropland expansion due for selected biofuel pathways

Biofuel case which induce land use changes		Biofuel produced (billion gallon)	New cropland needed (1000 ha.)	New cropland needed (ha./1000 gallons of biofuel)	New cropland needed (ha./1000 gallons of ethanol eq.)
(a)	Corn Ethanol	11.59	2078	0.18	0.18
(c)	Miscanthus Bio-gasoline	4.7	319	0.07	0.05
(d)	Switchgrass Bio-gasoline	4.7	775	0.16	0.11
(f)	Miscanthus Ethanol	7	408	0.06	0.06
(g)	Switchgrass Ethanol	7	1054	0.15	0.15

The detailed land use changes among cropland, forest, and pasture and in different global regions are needed to evaluate induced land use emissions. The work done by TTW provides these data items by region and AEZ and are available upon request.

3. EFs and their backgrounds

In general, research studies in this area have examined three major categories of LUC emissions released to the atmosphere due to biofuels: 1) CO_2 emissions due to changes in vegetation carbon stock; CO_2 emissions due to changes in soil carbon stock; and CO_2 emissions due to loss in carbon sequestration. These items tend to capture induced emissions as a result of deforestation due to biofuel expansion[2]. Many research studies in this area[3] relied on the vegetation and soil carbon data bases developed by the Woods Hole Research Center (WHRC), Winrock International (WI), or Intergovernmental Plan on Climate Change (IPCC) to estimate EFs. These data sets provide highly aggregated regional data on vegetation and soil carbon fluxes. More recently several attempts have been made to provide more detailed data on the vegetation and soil carbon fluxes. Zhuang et al. (2010) have produced a data set on carbon fluxes at the grid cell level using the Terrestrial Ecosystem Model (TEM) at a global scale. This data set can be used to develop land use emission factors at a regional level by Agro Ecological Zone (AEZ). Plevin et al. (2011) obtained a data set which measures land use emission factors for several types of vegetation areas divided into 19 regions by AEZ. The California Air Resource Board (CARB) is expected to use the land use emissions factors developed by these authors to assess the land use emissions due to biofuel pathways in defining California fuel standards. The emission factors mentioned above are analyzed in the rest of this section.

[2] This common classification ignores two important sources of induced LUC emissions: Non-CO_2 emissions due to changes in agricultural practices and changes in soil carbon sequestration.

[3] Examples are: Searchinger, et al., 2008; Hertel et al., 2010; Al-Riffai et al., 2010; Taheripour et al., 2010; and Tyner et al. 2010.

3.1. Woods Hole EFs

This data set divides the world into 10 aggregated regions and provides the following information for each region:

- Forest area by ecosystem in million hectares,
- Carbon in vegetation in metric ton per hectare,
- Carbon in soil in metric ton per hectare,
- Re-growing forest area in million hectares,
- Gross carbon uptake by re-growing forests in million metric tons carbon per year,
- Carbon uptake by forest area in metric ton carbon per hectare per year.

Several papers have used this data set in combination with their assumptions on carbon fluxes to obtain regional EFs. For example, Searchinger et al. (2008) and Tyner et al. (2010) assumed that about 25% of carbon stored in natural land will be released to the atmosphere when a natural land is converted to cropland. Another common assumption in this area is that a fixed portion of carbon stored in natural vegetation will be released to the atmosphere at the time of land conversion. For example, Tyner et al. (2010) assumed that 75% of carbon stored in the forest type vegetation and 100% percent of carbon stored in the grassland vegetation will be released into the atmosphere at the time of land conversion. The first three items listed above are used to calculate reductions in carbon stored in soil and vegetation of natural areas of each region. Furthermore, it is usually assumed that when a natural vegetation area (mainly forest) is converted to cropland, it loses its carbon sequestration capability as long as it is under crop production. The last three items listed above are usually used to quantify the forgone carbon sequestration. For example, Searchinger et al. (2008), Hertel et al. 2010, Tyner et al. (2010), and many other papers followed this tradition. Tyner et al. (2010) have explained the Woods Hole data set in detail and used a set of EFs for forest and pasture land based on this data set assuming that the converted natural land to cropland will remain under crop production for 30 years (life time for biofuel production). The EFs developed by these authors are presented in Table A1 of Appendix A. These EFs indicate that converting forest to cropland releases significantly larger CO_2 emissions compared to pasture land.

3.2. California Air Resources Board (CARB) EFs[4]

An expert working group at CARB concluded that improvements were needed in the Woods Hole data (Yeh, et al., 2010). To reduce EF uncertainties and eliminate inherent deficiencies in EFs obtained from Woods Hole data, the CARB has developed a new data set and a program which provide EFs for 18 Agro Ecological Zones (AEZ) in each region at a global scale (Plevin et al., 2011). The new CARB data set divides the world into 19 regions presented in GTAP-BIO model and includes the following sinks and sources of GHG emissions from LUC:

- Above-ground live biomass (trunks, branches, and foliage)
- Below-ground live biomass (coarse and fine roots),
- Dead organic matter (dead wood and litter),
- Soil organic matter
- Harvested wood products,
- Non-CO2 climate-active emissions (e.g. CH4 and N2O,
- Forgone sequestration.

These data items are collected from the existing data bases and literature and then in combination with a series of detailed assumptions on carbon fluxes, the CARB new EFs are calculated for the following main categories of land conversions: *i*) forest to cropland and reverse, *ii*) pasture to cropland and reverse, *iii*) cropland-pasture to cropland and reverse, *iv*) and pasture to forest and

[4] Neither the land use change estimates in this paper nor the emission factors have been approved by CARB. The authors are solely responsible for the paper's contents. The CARB emission factors are preliminary values prepared by Dr. Rich Plevin, but are not approved by CARB. We thank Dr. Plevin for his help with the factors.

reverse. Unlike the EFs developed based on Woods Hole data, the CARB EFs for converting one type of land to another type and their reverse are not identical. For example, the EFs for converting forest to cropland and returning croplands to forest are not identical for the same region-AEZ. Tables A2.1to A2.8 of Appendix A contain the new CARB EFs. These tables indicate that the EFs vary significantly across regions and AEZs. In addition they show that EFs of forest to cropland > EFs of forest to pasture land > EFs of pasture land to cropland > EFs of cropland pasture to cropland.

The new CARB EFs are built based on several research data bases on carbon pools and considers many information sources. Furthermore, the assumptions which are used to convert carbon pools to EFs are carefully selected based on evidence from the literature. The carbon pools used in developing the new CARB EFs factors are taken from several data bases which represent different biophysical modeling frameworks and assumptions. Hence, they may not be perfectly matched.

3.3. TEM EFs

The EFs which are developed to date have three main components: carbon stock in soil, carbon stock in vegetation, and forgone carbon sequestration. Zhuang et al. (2009) have generated a data set which provides data on soil and vegetation carbon pools and Net Primary Production (NPP) at an 0.5^o x 0.5^o (latitude by longitude) spatial resolution. The TEM model, a process-based biogeochemistry model, is used to develop this data set. These authors have developed illustrative EFs for the US economy at AEZ level based on the outputs of the TEM model. This section follows the approach provided by these authors and develops a set of regional EFs at the AEZ level using the outputs of the TEM model in combination with assumptions on carbon fluxes. To establish a base case, a set of TEM EFs is developed with the common assumptions which have been used earlier in several research studies. The base case assumptions are:

a. At the time of land conversion (either from forest of pasture land to cropland) 25% of carbon stored in soils will be released to the atmosphere,

b. At the time of land conversion 75% of carbon stored in forest vegetation (above and underground) will be released to the atmosphere,
c. At the time of land conversion 100% of carbon stored in pasture land vegetation (above and underground) will be released to the atmosphere,
d. Forgone forest carbon sequestration is equal to 25% of annual NPP,
e. No Forgone carbon sequestration for pasture land and cropland pasture,
f. EFs for converting cropland pasture to cropland are 50% of those for converting pasture land to cropland.

The TEM EFs under these base case assumptions are shown in tables A3.1 to A3.3. Comparing these EFs with their CARB corresponding EFs indicates that in many cases, in particular for forest EFs, these two sources represent relatively similar EFs. However, major differences can be observed, in particular, among pastureland EFs. Two factors can explain differences between TEM and CARB EFs. First, these EFs could be different because they use different carbon pools. Second, CARB uses more detailed regional assumptions on carbon fluxes compared to the simple assumptions used for the TEM case. In the rest of this paper we calculate induced LUC emissions for several biofuel pathways using the EFs presented in this section.

4. Induced LUC emissions and sensitivity tests

In this section we first calculate induced LUC emissions for the biofuel pathways presented in Table 1 in combination with the EFs obtained based on Woods Hole, CARB and TEM data bases. Then we test the sensitivity of results obtained from the TEM EFs with respect to changes in the base assumptions used in derivation of these EFs. Table 3 presents the estimated land use emissions.

First consider the results for a case where we assume converting cropland pasture to cropland (either for producing traditional crops or dedicated energy crops) has no land use emissions (see the first three numerical columns of table 3). The results indicate that the estimated induced land use emissions vary across alternative sets of EFs and biofuels. In general, regardless of biofuel type, the Woods Hole EFs generate the lowest land use emissions and the TEM EFs predict the highest emissions. The estimated emissions obtained from the CARB and TEM EFs generally are not very different. Among alternative biofuels, corn stover ethanol and corn stover bio-gasoline do not have land use emissions because there is little land use change. However, any change in soil carbon due to residue removal has not been considered. Miscanthus bio-gasoline and switchgrass ethanol have the lowest and highest land use emissions, respectively. For example, with the CARB EFs these fuels cause about 7.1 g CO2e $MJ^{-1}$and 35.5 g CO2e MJ^{-1} emissions. The estimated emissions for corn ethanol are about 15.1 g CO2e MJ^{-1}. Finally, the ethanol pathway consistently has higher land use changes and higher emissions than the thermochemical pathway. The emissions increase is substantially higher for the CARB and TEM emission factors because of the higher land use change, because of the large proportion of the increase that comes from forestry, and because the CARB and TEM factors are more detailed and better able to associate the land use changes in the actual AEZ/region from GTAP.

We now present changes in induced LUC emissions if we assume converting cropland pasture to cropland causes land use emissions. Indeed, in this test we adopt the CARB logic which assumes converting cropland pasture to crop production generate land use emissions and that the EF for converting cropland pasture to cropland is about 50% of the EF of converting pasture land to cropland. Adopting this assumption increases the estimates for induced land use emissions for biofuels produced from corn, miscanthus, and switchgrass significantly (see the last three columns of Table 3 and Figure 1). In particular, emissions due to fuels produced from dedicated crops escalate largely due to adopting this assumption. For example, with the CARB

EFs the estimated emissions for miscanthus bio-gasoline and switchgrass ethanol elevate from 7.1 g CO2e $MJ^{-1}$and 35.5 g CO2e MJ^{-1} to 19.4 CO2e MJ^{-1} and 63 CO2e MJ^{-1}, respectively. This rate for corn ethanol goes up moderately from 15.1 g CO2e MJ^{-1} to 18 g CO2e MJ^{-1}.

Table 3. Estimated induced land use emissions due to biofuel production for alternative land use emissions factors (g CO_2e MJ^{-1})

Case	Feedstock	Biofuel	Without CP-EF[1]			With CP-EF[2]		
			WH[3]	CARB[4]	TEM[5]	WH[3]	CARB[4]	TEM[4]
(a)	Corn	Ethanol	12.9	15.1	17.0	15.5	18	22.6
(b)	Corn stover	Bio-gasoline	-1.0	-1	-1.1	-1.0	-1	-1.1
(c)	Miscanthus	Bio-gasoline	6.1	7.1	7.3	18.1	19.4	25.6
(d)	Switchgrass	Bio-gasoline	21.4	24.9	23.4	43.7	47.6	57.0
(e)	Corn stover	Ethanol	-1.0	-1.4	-1.5	-0.9	-1.4	-1.6
(f)	Miscanthus	Ethanol	5.8	10.1	10.1	15.7	25.4	32.3
(g)	Switchgrass	Ethanol	20.3	35.5	33.1	38.2	63	74.0

1- It is assumed that converting cropland pasture to cropland (either for producing traditional crop or dedicated energy crops) does not cause land use emissions.
2- It is assumed that converting cropland pasture to cropland (either for producing traditional crop or dedicated energy crops) causes land use emissions.
3- Based on EFs obtained from the Woods Hole data set.
4- Based on CARB EFs.
5- Based on the TEM EFs obtained for the base case assumption.

Adopting this assumption also increases the gap between the estimated emissions obtained from different sources of EFs. Table 4 illustrate percentage changes in estimated emissions obtained from the CARB and TEM EFs compared with their WH corresponding figures for the cases with and without cropland pasture. This table shows that corn ethanol emissions increase 32% using TEM and 46% if cropland pasture is included. CARB increases are about half those levels. Bio-gasoline has the smallest differences among the three EFs. Miscanthus is 20% higher with TEM and 16% with CARB, while switchgrass is 9% higher with TEM and 16% with CARB. Inclusion of cropland pasture substantially increases the emissions – by 41% for Miscanthus and 30% for switchgrass. The biggest variation is for ethanol for the same reasons as in the previous case. Without cropland pasture, emissions increase 74% and

63% for miscanthus and switchgrass for TEM and somewhat similar levels for CARB. With cropland pasture, the miscanthus increase is 106% for miscanthus and 94% for TEM. For CARB, the increases are 62% and 65% respectively. Again, this is because much of the land use change for cropland pasture is in AEZs with higher emission factors.

These results lead us to two important deficiencies in this area. A common assumption is that converting cropland pasture to cropland has zero land use emission. Recently, Pleven et al. (2011) in developing CARB EFs have assumed that converting cropland pasture to crop production causes land use emissions. In the absence of reliable data in this area, these authors assumed that in each region-AEZ the EF for converting cropland pasture to cropland is about 50% of EF for converting pasture land to cropland. The above comparison shows that this ad hoc assumption could significantly change the results, in particular for the second generation biofuels produced from dedicated crops, which are assumed to be grown on marginal land such as cropland pasture. Adequate and reliable data is needed to develop EFs for cropland pasture areas.

Table 4. Percentage changes in estimated land use emissions obtained from CARB or TEM compared to Woods Hole (%)

Case	Feedstock	Biofuel	Without CP-EF			With CP-EF		
			WH	CARB	TEM	WH	CARB	TEM
(a)	Corn	Ethanol	0.0	17.1	31.8	0.0	16.1	45.8
(c)	Miscanthus	Bio-gasoline	0.0	16.4	19.7	0.0	7.2	41.4
(d)	Switchgrass	Bio-gasoline	0.0	16.4	9.3	0.0	8.9	30.4
(f)	Miscanthus	Ethanol	0.0	74.1	74.1	0.0	61.8	105.7
(g)	Switchgrass	Ethanol	0.0	74.9	63.1	0.0	64.9	93.7

In developing EFs it is assumed that a portion of soil carbon stock will be released to the atmosphere at the time deforestation due to biofuels. However, the fact that soil carbon sequestration capability can also change due to changes in vegetation cover is ignored in this area. Several papers have shown that converting cropland or grassland to production of dedicated energy crops such as miscanthus and switchgrass can increase soil carbon content (for example, see Anderson-Teixeira et al., 2009). Taking this factor into account could significantly affect the magnitude of estimates of LUC emissions due to biofuels, in particular for cellulosic materials.

We now examine sensitivity of estimated LUC emissions with respect to changes in the common assumptions on carbon fluxes which are used in developing all types of EFs. For this test we stay with the assumption that cropland pasture conversion does not cause land use emissions. We observed that under this assumption the CARB and TEM emissions factors lead to somewhat similar estimates for induced land use emissions for every biofuel examined in this paper. Given this fact and given that the assumptions behind the CARB emissions factors are very detailed, in this test we only examine the sensitivity of results with respect to changes in the base case assumptions used in construction of the TEM EFs. For this purpose we defined the following tests:

Test 1

- Reduction in rate of soil carbon release from 25% to 15%,
- Reduction in rate of vegetation carbon release from 75% to 65% for forest areas and 100% to 90% for pasture areas,
- Reduction in rate of forgone sequestration from 25% to 15%,

Test 2

- Increase in rate of soil carbon release from 25% to 35%,
- Increase in rate of vegetation carbon release from 75% to 85% for forest area and no changes for pasture area.
- Increase in rate of forgone sequestration from 25% to 35%,

The induced LUC emissions are calculated for each of these two tests in combination with induced LUCs reported in Table 1 for all biofuels except for corn stover biofuels which do not generate LUC emissions. The results are presented in Table 5. For test one, the reduction in emissions ranged between -9% and -28%. For test two, the increases in emissions ranged between 13% and 29%. These figures confirm that the estimated induced LUC emissions are sensitive to changes in our assumptions on the rates for carbon fluxes.

Table 5. Sensitivity of TEM estimated induced land use emissions with respect to changes in assumed rates of carbon fluxes for selected biofuel pathways

Biofuel pathway	Induced LUC emissions in g CO_2e MJ^{-1}			Percent changes compared to base case		
	Base Case	*Test 1*	*Test 2*	*Base Case*	*Test 1*	*Test 2*
(a)	15.1	13.7	19.4	0.0	-9.3	28.5
(c)	7.1	5.8	8.7	0.0	-18.3	22.5
(d)	24.9	18.2	28.4	0.0	-26.9	14.1
(f)	10.1	8.0	12.1	0.0	-20.8	19.8
(g)	35.5	25.7	40.1	0.0	-27.6	13.0

5. Conclusions

Uncertainties in EFs are examined from three different aspects. We first showed that the Woods Hole, CARB, and TEM EFs are different because their sources on carbon pools are different. In general, the Woods Hole EFs are smaller than the CARB and TEM EFs. The CARB and TEM forest emissions factors are close in many cases, but major differences are observed as well. The pasture land EFs of these two sources are significantly different in many cases. In general, the TEM EFs for pasture land are larger than their CARB corresponding figures.

Then we examined the CARB assumption that converting cropland pasture to cropland generates land use emissions and that the EFs for this type of land conversion are about 50% of EFs of pasture land. We observed that adopting this assumption increases the estimated induced

LUC emissions obtained from all types of EFs for biofuel pathways which induce LUCs, in particular for the second generation of biofuels, which mainly use dedicated crops produced on cropland pasture areas in the US. Finally we observed that the results are very sensitive with respect to the changes in the common assumptions about the rates of carbon fluxes.

The two major conclusions from this emissions analysis are: 1) inclusion or exclusion of cropland pasture makes a huge difference; and 2) there is wide divergence among the emission factor sources, especially for dedicated crop conversion to ethanol. Inclusion of cropland pasture emissions doubles or triples the emissions obtained using the Woods Hole factors. The estimated induced land use emissions for ethanol and bio-gasoline produced from dedicated crops are essentially the same using the WH EFs, but vastly different using the CARB or TEM EFs factors, with cellulosic ethanol producing substantially more emissions.

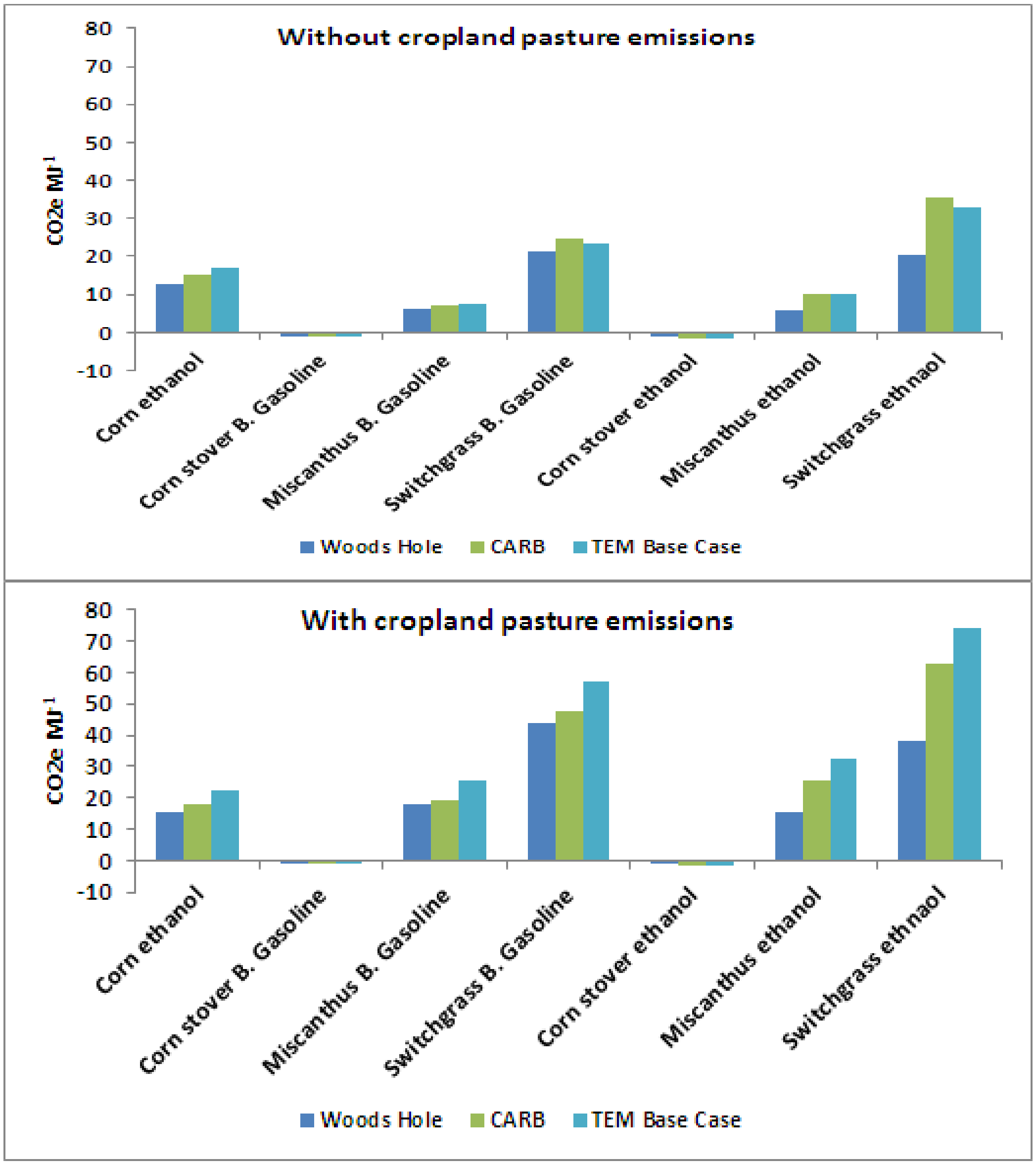

Figure 1. Induced land use emissions with and without cropland pasture emissions

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Appendix A

Land Use Emissions Factors

Table A1. Emissions factors obtained from Woods Hole data sets. for forest and grassland areas* (Mg CO_2 $ha^{-1}y^{-1}$)

Regions	Forest emissions factors	Grassland emissions factors	Cropland pasture emissions factors
United States	19.6	3.7	1.85
Canada	15.3	5.7	2.8
Sub Saharan Africa	10.4	1.5	0.75
European Union 27 East Europe and Rest of Former Soviet Union Rest of European Countries	18.6	6.6	3.3
Russia	14.1	7.0	3.5
Brazil Central and Caribbean Americas South and Other Americas	16.1	2.5	1.25
Middle Eastern and North Africa	12.2	2.2	1.1
East Asia Oceania Japan	13.2	3.5	1.75
China and Hong Kong India	23.0	6.6	3.3
Rest of South East Asia Rest of South Asia Malaysia and Indonesia	23.0	6.6	3.3

*Assumptions:
25% of carbon released from soil during land conversion;
75% of carbon released from vegetation for forest conversion;
100 % of carbon released from vegetation for grassland conversion;
30 years considered in calculating foregone sequestration;
A conversion factor of 3.67 is used to convert of C to CO2 equivalent per hectare;
Cropland pasture emissions factors are equal to 50% of emissions factors for grass land.
Source: Tyner et al. (2010).

Table A2.1. CARB land use emissions factors for forest-to-cropland (Mg CO_2 $ha^{-1}y^{-1}$)

AEZ/Region	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.0	0.0	11.2	0.0	0.0	0.0	9.8	10.9	13.6	0.0	0.0	0.0	10.3	0.0	0.0	0.0	14.4	16.9	14.4
2	0.0	0.0	9.8	0.0	0.0	0.0	14.4	20.0	19.0	0.0	0.0	0.0	7.0	0.0	0.0	0.0	16.2	21.3	15.4
3	0.0	0.0	17.9	0.0	0.0	0.0	20.8	21.6	16.6	0.0	0.0	0.0	19.5	0.0	0.0	0.0	14.2	19.7	25.0
4	0.0	7.9	24.5	0.0	0.0	0.0	26.7	35.2	21.4	21.6	63.3	29.2	22.7	0.0	0.0	0.0	16.0	21.8	29.0
5	0.0	0.0	32.0	0.0	0.0	28.1	28.7	37.3	25.4	21.2	61.4	30.3	27.1	0.0	0.0	0.0	0.0	29.3	28.9
6	0.0	0.0	34.6	0.0	0.0	26.8	32.6	35.4	31.4	22.7	65.2	30.7	27.2	0.0	0.0	0.0	0.0	35.6	30.1
7	15.6	0.0	0.0	12.9	0.0	12.4	7.4	29.0	10.9	9.0	0.0	0.0	11.9	12.8	17.0	0.0	18.8	20.0	16.3
8	20.4	10.7	0.0	15.3	0.0	11.8	13.0	29.7	10.9	10.6	0.0	0.0	16.7	13.3	19.4	0.0	17.4	19.5	17.2
9	21.9	17.3	0.0	17.0	20.4	10.5	20.5	21.9	13.2	10.0	0.0	0.0	18.7	15.7	14.0	16.5	15.9	19.5	16.8
10	24.7	14.4	16.7	22.7	20.3	9.7	22.7	20.7	17.0	9.0	0.0	22.9	27.0	16.2	11.8	14.6	16.4	18.7	22.0
11	23.8	13.4	12.3	24.0	20.9	19.5	31.5	22.7	17.6	14.7	0.0	28.2	33.3	12.8	10.8	14.7	0.0	19.1	22.2
12	18.0	16.6	17.4	0.0	21.0	25.2	36.6	25.7	20.5	23.6	0.0	29.8	35.5	14.0	14.8	0.0	0.0	20.7	25.0
13	18.5	10.9	0.0	10.9	0.0	23.6	28.2	0.0	15.3	11.3	0.0	0.0	23.2	11.5	10.9	14.6	0.0	0.0	0.0
14	20.6	14.8	0.0	11.5	0.0	23.4	21.5	0.0	18.5	11.9	0.0	0.0	23.3	14.4	12.4	11.2	0.0	0.0	0.0
15	28.3	18.1	0.0	15.3	15.6	25.5	24.5	0.0	18.1	13.0	0.0	28.1	29.8	15.9	12.7	14.1	0.0	0.0	18.5
16	43.3	21.3	0.0	20.0	0.0	27.6	29.1	0.0	23.8	0.0	0.0	35.4	34.0	16.8	18.2	17.5	0.0	0.0	22.7
17	0.0	0.0	0.0	0.0	0.0	28.0	0.0	0.0	25.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	29.6
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	22.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source: Pleven et al. (2011)

Table A2.2. CARB land use emissions factors for pasture-to-cropland (Mg CO_2 $ha^{-1}y^{-1}$)

AEZ/Region	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.0	0.0	2.0	0.0	0.0	0.0	1.4	1.8	2.5	0.0	0.0	0.0	1.9	0.0	0.0	0.0	2.0	1.6	2.0
2	0.0	0.0	1.9	0.0	0.0	0.0	2.4	5.3	1.4	0.0	0.0	0.0	1.9	0.0	0.0	0.0	2.0	1.9	2.2
3	0.0	0.0	2.3	0.0	0.0	0.0	2.2	4.8	1.0	0.0	0.0	0.0	2.2	0.0	0.0	0.0	1.8	2.2	2.1
4	0.0	4.8	3.4	0.0	0.0	0.0	3.0	8.1	5.8	4.7	3.9	3.2	4.3	0.0	0.0	0.0	2.6	3.2	3.3
5	0.0	0.0	3.4	0.0	0.0	5.1	3.6	6.4	5.9	4.1	4.0	3.3	3.8	0.0	0.0	0.0	0.0	3.2	1.9
6	0.0	0.0	3.3	0.0	0.0	3.5	3.8	6.1	10.3	4.0	5.4	3.5	3.5	0.0	0.0	0.0	0.0	3.4	6.6
7	3.4	0.0	0.0	3.5	0.0	3.5	2.1	5.5	3.1	3.6	0.0	0.0	2.2	3.4	2.8	0.0	2.5	1.3	2.5
8	3.7	3.1	0.0	4.1	0.0	3.4	2.8	5.8	3.2	4.0	0.0	0.0	2.1	4.4	2.4	0.0	2.6	1.4	2.7
9	3.8	3.6	0.0	13.6	13.0	2.7	2.9	5.1	4.8	3.0	0.0	0.0	2.2	5.4	3.2	3.9	2.7	2.3	2.5
10	4.3	12.5	4.8	7.4	11.5	3.5	3.6	13.2	4.4	3.5	0.0	3.8	3.4	10.5	3.5	6.5	3.4	2.8	3.8
11	3.7	9.8	2.6	3.8	11.4	3.9	3.8	5.0	4.6	3.5	0.0	3.8	6.1	5.1	4.0	6.8	0.0	2.8	4.2
12	3.4	15.4	5.2	0.0	11.4	4.2	3.6	17.1	6.5	4.7	0.0	3.8	9.9	5.3	3.4	0.0	0.0	2.2	6.6
13	1.5	1.6	0.0	1.4	0.0	2.2	0.7	0.0	2.7	1.5	0.0	0.0	1.1	1.6	1.6	1.1	0.0	0.0	0.0
14	1.6	1.7	0.0	1.7	0.0	2.1	1.3	0.0	2.6	2.1	0.0	0.0	1.1	1.8	1.7	0.8	0.0	0.0	0.0
15	2.9	2.0	0.0	2.9	4.1	2.4	1.2	0.0	1.3	2.5	0.0	1.1	1.5	2.6	1.9	1.4	0.0	0.0	1.7
16	5.8	10.6	0.0	5.9	0.0	3.2	2.0	0.0	1.4	0.0	0.0	2.0	2.1	3.0	2.6	6.5	0.0	0.0	2.3
17	0.0	0.0	0.0	0.0	0.0	2.9	0.0	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source: Pleven et al. (2011)

Table A2.3. CARB land use emissions factors for cropland pasture-to-cropland (Mg CO_2 $ha^{-1}y^{-1}$)

AEZ/Region	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.0	0.0	1.0	0.0	0.0	0.0	0.7	0.9	1.3	0.0	0.0	0.0	1.0	0.0	0.0	0.0	1.0	0.8	1.0
2	0.0	0.0	0.9	0.0	0.0	0.0	1.2	2.6	0.7	0.0	0.0	0.0	1.0	0.0	0.0	0.0	1.0	1.0	1.1
3	0.0	0.0	1.1	0.0	0.0	0.0	1.1	2.4	0.5	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.9	1.1	1.1
4	0.0	2.4	1.7	0.0	0.0	0.0	1.5	4.1	2.9	2.4	2.0	1.6	2.1	0.0	0.0	0.0	1.3	1.6	1.7
5	0.0	0.0	1.7	0.0	0.0	2.6	1.8	3.2	3.0	2.1	2.0	1.7	1.9	0.0	0.0	0.0	0.0	1.6	1.0
6	0.0	0.0	1.7	0.0	0.0	1.7	1.9	3.1	5.2	2.0	2.7	1.8	1.7	0.0	0.0	0.0	0.0	1.7	3.3
7	1.7	0.0	0.0	1.8	0.0	1.8	1.0	2.8	1.5	1.8	0.0	0.0	1.1	1.7	1.4	0.0	1.3	0.6	1.2
8	1.8	1.5	0.0	2.0	0.0	1.7	1.4	2.9	1.6	2.0	0.0	0.0	1.1	2.2	1.2	0.0	1.3	0.7	1.3
9	1.9	1.8	0.0	6.8	6.5	1.4	1.4	2.6	2.4	1.5	0.0	0.0	1.1	2.7	1.6	1.9	1.4	1.1	1.3
10	2.2	6.3	2.4	3.7	5.7	1.7	1.8	6.6	2.2	1.8	0.0	1.9	1.7	5.3	1.8	3.2	1.7	1.4	1.9
11	1.9	4.9	1.3	1.9	5.7	2.0	1.9	2.5	2.3	1.7	0.0	1.9	3.0	2.5	2.0	3.4	0.0	1.4	2.1
12	1.7	7.7	2.6	0.0	5.7	2.1	1.8	8.5	3.2	2.3	0.0	1.9	4.9	2.6	1.7	0.0	0.0	1.1	3.3
13	0.7	0.8	0.0	0.7	0.0	1.1	0.4	0.0	1.4	0.7	0.0	0.0	0.6	0.8	0.8	0.6	0.0	0.0	0.0
14	0.8	0.9	0.0	0.9	0.0	1.0	0.6	0.0	1.3	1.0	0.0	0.0	0.5	0.9	0.8	0.4	0.0	0.0	0.0
15	1.4	1.0	0.0	1.5	2.1	1.2	0.6	0.0	0.6	1.3	0.0	0.5	0.7	1.3	0.9	0.7	0.0	0.0	0.9
16	2.9	5.3	0.0	2.9	0.0	1.6	1.0	0.0	0.7	0.0	0.0	1.0	1.1	1.5	1.3	3.2	0.0	0.0	1.2
17	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source: Pleven et al. (2011)

Table A2.4. CARB land use emissions factors for pasture-to-forest (Mg CO_2 $ha^{-1}y^{-1}$)

AEZ/Region	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.0	0.0	-5.4	0.0	0.0	0.0	-4.7	-5.6	-7.9	0.0	0.0	0.0	-5.2	0.0	0.0	0.0	-8.3	-8.3	-7.6
2	0.0	0.0	-5.1	0.0	0.0	0.0	-9.2	-7.7	-10.1	0.0	0.0	0.0	-3.8	0.0	0.0	0.0	-8.3	-8.3	-7.8
3	0.0	0.0	-9.2	0.0	0.0	0.0	-15.8	-11.5	-10.1	0.0	0.0	0.0	-14.3	0.0	0.0	0.0	-8.3	-8.6	-15.5
4	0.0	-0.3	-12.1	0.0	0.0	0.0	-15.2	-11.6	-15.2	-14.5	-19.7	-15.2	-15.2	0.0	0.0	0.0	-7.9	-9.8	-19.1
5	0.0	0.0	-19.0	0.0	0.0	-15.2	-15.2	-13.6	-18.0	-14.3	-17.9	-15.2	-15.2	0.0	0.0	0.0	0.0	-16.6	-16.9
6	0.0	0.0	-21.6	0.0	0.0	-15.2	-15.2	-18.2	-22.0	-15.2	-23.4	-15.2	-15.2	0.0	0.0	0.0	0.0	-20.5	-21.9
7	-11.6	0.0	0.0	-8.3	0.0	-6.8	-4.5	-8.2	-6.4	-4.4	0.0	0.0	-7.9	-8.1	-5.3	0.0	-8.3	-8.3	-11.3
8	-13.2	-6.2	0.0	-9.2	0.0	-7.9	-8.5	-8.6	-6.5	-5.8	0.0	0.0	-12.4	-8.8	-9.1	0.0	-8.3	-8.3	-11.3
9	-13.2	-8.1	0.0	-9.6	-9.8	-6.4	-12.4	-7.4	-8.1	-5.1	0.0	0.0	-12.4	-9.0	-10.4	-6.9	-8.3	-9.5	-11.3
10	-12.0	-6.3	-10.6	-8.9	-8.9	-5.3	-11.2	-8.5	-11.0	-3.9	0.0	-11.2	-11.2	-7.7	-5.2	-7.3	-7.1	-8.2	-10.1
11	-12.0	-7.1	-8.2	-8.3	-8.9	-15.4	-11.2	-10.5	-11.0	-5.2	0.0	-11.2	-11.2	-8.2	-5.7	-10.3	0.0	-8.8	-10.1
12	-11.3	-7.1	-11.1	0.0	-8.9	-17.1	-11.2	-11.2	-12.0	-8.9	0.0	-11.2	-11.2	-2.1	-10.8	0.0	0.0	-10.7	-10.1
13	-6.7	-5.6	0.0	-7.3	0.0	-7.1	-7.1	0.0	-7.1	-6.8	0.0	0.0	-7.1	-7.1	-7.0	-7.1	0.0	0.0	0.0
14	-6.7	-5.6	0.0	-6.5	0.0	-7.1	-7.1	0.0	-7.1	-7.0	0.0	0.0	-7.1	-7.1	-7.1	-5.9	0.0	0.0	0.0
15	-6.7	-5.6	0.0	-8.1	-7.1	-7.1	-7.1	0.0	-7.1	-7.1	0.0	-7.1	-7.1	-7.1	-7.1	-7.1	0.0	0.0	-7.1
16	-9.0	-8.0	0.0	-10.4	0.0	-9.5	-9.5	0.0	-9.5	0.0	0.0	-9.5	-9.5	-9.5	-9.5	-9.5	0.0	0.0	-9.5
17	0.0	0.0	0.0	0.0	0.0	-9.5	0.0	0.0	-9.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-9.5
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-9.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source: Pleven et al. (2011)

Table A2.5. CARB land use emissions factors for cropland-to-forest (Mg CO_2 $ha^{-1}y^{-1}$)

AEZ/Region	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0	0	-12.9	0	0	0	-11.3	-13.3	-16.6	0	0	0	-12.4	0	0	0	-12.1	-11.1	-16.2
2	0	0	-12.5	0	0	0	-17.1	-14	-17.6	0	0	0	-11.1	0	0	0	-11.6	-11.4	-16.7
3	0	0	-18.2	0	0	0	-22.7	-25.8	-16.9	0	0	0	-23.2	0	0	0	-12.1	-15.7	-20.4
4	0	-8.67	-21.3	0	0	0	-21.2	-35.2	-27.2	-24.6	-31.1	-21.6	-23.8	0	0	0	-14	-20	-30
5	0	0	-28.9	0	0	-23.4	-22.5	-30.6	-33.5	-22.8	-32.6	-21.6	-25	0	0	0	0	-27	-27.4
6	0	0	-29.3	0	0	-22.7	-22.6	-40	-52.4	-24.6	-35.1	-23.5	-25.7	0	0	0	0	-27.7	-37.3
7	-15	0	0	-16	0	-12.2	-9.42	-14	-10.8	-10	0	0	-12.9	-13.7	-10.9	0	-9.75	-9.09	-12.5
8	-15.3	-10.5	0	-16.5	0	-13.7	-13.4	-14.9	-11.6	-11.3	0	0	-13.8	-14.7	-14.7	0	-9.81	-9.05	-12.6
9	-15.4	-10.3	0	-18.4	-14.6	-12.1	-13.9	-13.9	-11.8	-10.6	0	0	-13.6	-14.7	-14.9	-12.9	-9.89	-12.8	-12.5
10	-16.1	-12.3	-17.9	-17.4	-17.8	-10.9	-14.1	-18.2	-19.1	-9.8	0	-14.2	-13.6	-15.6	-13.8	-17.4	-10.1	-13.3	-12.9
11	-15.5	-10.9	-14.6	-17.3	-19.6	-20.3	-15.2	-26.1	-23.2	-11.1	0	-14.5	-13.7	-16.3	-12.4	-18.8	0	-13.5	-13.4
12	-17.9	-10.6	-17.3	0	-12.7	-20.4	-14.3	-19.8	-17.4	-12.3	0	-14.6	-14.2	-10.4	-15	0	0	-15.8	-13.4
13	-8.76	-8.26	0	-10.1	0	-9.99	-7.96	0	-9.3	-9.75	0	0	-8.68	-9.12	-9.57	-10.1	0	0	0
14	-8.54	-8.29	0	-8.53	0	-9.56	-8.02	0	-9.3	-9.75	0	0	-8.64	-9.34	-9.64	-11.9	0	0	0
15	-8.82	-14.2	0	-12.3	-13.5	-9.97	-8.92	0	-8.93	-9.72	0	-9.97	-10.1	-9.78	-9.42	-11.9	0	0	-8.51
16	-12.7	-11.5	0	-21.7	0	-12.9	-12.9	0	-11.9	0	0	-12.3	-11.8	-13.1	-13	-15	0	0	-12
17	0	0	0	0	0	-11.7	0	0	-12.1	0	0	0	0	0	0	0	0	0	-12.6
18	0	0	0	0	0	0	0	0	-12.8	0	0	0	0	0	0	0	0	0	0

Source: Pleven et al. (2011)

Table A2.6. CARB land use emissions factors for cropland-to-pasture (Mg CO_2 $ha^{-1}y^{-1}$)

AEZ/Region	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.0	0.0	-3.2	0.0	0.0	0.0	-2.2	-3.5	-6.0	0.0	0.0	0.0	-2.9	0.0	0.0	0.0	-3.3	-2.3	-4.3
2	0.0	0.0	-3.1	0.0	0.0	0.0	-3.7	-3.4	-7.0	0.0	0.0	0.0	-3.0	0.0	0.0	0.0	-2.8	-2.6	-4.6
3	0.0	0.0	-4.8	0.0	0.0	0.0	-3.7	-10.0	-6.3	0.0	0.0	0.0	-4.6	0.0	0.0	0.0	-3.4	-3.3	-4.4
4	0.0	-7.2	-4.9	0.0	0.0	0.0	-5.5	-19.2	-7.7	-8.9	-7.1	-5.9	-8.1	0.0	0.0	0.0	-5.6	-5.8	-7.6
5	0.0	0.0	-6.4	0.0	0.0	-7.7	-6.8	-12.7	-11.1	-7.1	-10.3	-5.9	-9.3	0.0	0.0	0.0	0.0	-6.1	-6.3
6	0.0	0.0	-6.9	0.0	0.0	-7.1	-6.9	-17.5	-29.9	-8.9	-9.4	-7.8	-10.0	0.0	0.0	0.0	0.0	-6.8	-14.9
7	-1.7	0.0	0.0	-1.7	0.0	-2.0	-1.1	-2.0	-1.5	-1.8	0.0	0.0	-1.2	-2.0	-1.8	0.0	-1.3	-0.7	-1.1
8	-2.0	-2.1	0.0	-1.8	0.0	-2.0	-1.1	-2.5	-1.3	-1.8	0.0	0.0	-1.2	-2.3	-2.2	0.0	-1.4	-0.6	-1.2
9	-2.0	-1.9	0.0	-3.7	-4.3	-1.9	-1.3	-2.7	-1.6	-1.7	0.0	0.0	-1.0	-2.3	-2.4	-2.2	-1.5	-0.7	-1.2
10	-4.0	-5.1	-4.3	-3.9	-8.8	-2.6	-2.8	-6.8	-5.1	-2.9	0.0	-2.9	-2.2	-5.1	-5.7	-7.1	-2.8	-2.0	-2.7
11	-3.3	-3.7	-3.4	-3.9	-10.5	-2.8	-3.9	-14.7	-9.2	-2.9	0.0	-3.1	-2.4	-5.3	-3.7	-7.4	0.0	-1.7	-3.2
12	-2.8	-3.4	-3.2	0.0	-3.6	-2.9	-2.9	-8.4	-3.0	-3.2	0.0	-3.3	-2.8	-5.5	-3.6	0.0	0.0	-2.1	-3.2
13	-2.0	-2.5	0.0	-1.9	0.0	-2.7	-0.7	0.0	-2.0	-2.5	0.0	0.0	-1.4	-2.0	-2.3	-2.9	0.0	0.0	0.0
14	-1.7	-2.5	0.0	-2.0	0.0	-2.3	-0.8	0.0	-2.0	-2.5	0.0	0.0	-1.4	-2.3	-2.4	-4.7	0.0	0.0	0.0
15	-2.0	-8.4	0.0	-4.1	-6.2	-2.7	-1.7	0.0	-1.7	-2.5	0.0	-2.7	-2.9	-2.7	-2.2	-4.6	0.0	0.0	-1.2
16	-3.6	-3.4	0.0	-11.2	0.0	-3.3	-3.3	0.0	-2.4	0.0	0.0	-2.8	-2.2	-3.7	-3.4	-5.4	0.0	0.0	-2.4
17	0.0	0.0	0.0	0.0	0.0	-2.1	0.0	0.0	-2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-3.0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-3.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source: Pleven et al. (2011)

Table A2.7. CARB land use emissions factors for cropland-to-cropland pasture (Mg CO_2 $ha^{-1}y^{-1}$)

AEZ/Region	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.0	0.0	-1.0	0.0	0.0	0.0	-0.7	-0.9	-1.3	0.0	0.0	0.0	-1.0	0.0	0.0	0.0	-1.0	-0.8	-1.0
2	0.0	0.0	-0.9	0.0	0.0	0.0	-1.2	-2.6	-0.7	0.0	0.0	0.0	-1.0	0.0	0.0	0.0	-1.0	-1.0	-1.1
3	0.0	0.0	-1.1	0.0	0.0	0.0	-1.1	-2.4	-0.5	0.0	0.0	0.0	-1.1	0.0	0.0	0.0	-0.9	-1.1	-1.1
4	0.0	-2.4	-1.7	0.0	0.0	0.0	-1.5	-4.1	-2.9	-2.4	-2.0	-1.6	-2.1	0.0	0.0	0.0	-1.3	-1.6	-1.7
5	0.0	0.0	-1.7	0.0	0.0	-2.6	-1.8	-3.2	-3.0	-2.1	-2.0	-1.7	-1.9	0.0	0.0	0.0	0.0	-1.6	-1.0
6	0.0	0.0	-1.7	0.0	0.0	-1.7	-1.9	-3.1	-5.2	-2.0	-2.7	-1.8	-1.7	0.0	0.0	0.0	0.0	-1.7	-3.3
7	-1.7	0.0	0.0	-1.8	0.0	-1.8	-1.0	-2.8	-1.5	-1.8	0.0	0.0	-1.1	-1.7	-1.4	0.0	-1.3	-0.6	-1.2
8	-1.8	-1.5	0.0	-2.0	0.0	-1.7	-1.4	-2.9	-1.6	-2.0	0.0	0.0	-1.1	-2.2	-1.2	0.0	-1.3	-0.7	-1.3
9	-1.9	-1.8	0.0	-6.8	-6.5	-1.4	-1.4	-2.6	-2.4	-1.5	0.0	0.0	-1.1	-2.7	-1.6	-1.9	-1.4	-1.1	-1.3
10	-2.2	-6.3	-2.4	-3.7	-5.7	-1.7	-1.8	-6.6	-2.2	-1.8	0.0	-1.9	-1.7	-5.3	-1.8	-3.2	-1.7	-1.4	-1.9
11	-1.9	-4.9	-1.3	-1.9	-5.7	-2.0	-1.9	-2.5	-2.3	-1.7	0.0	-1.9	-3.0	-2.5	-2.0	-3.4	0.0	-1.4	-2.1
12	-1.7	-7.7	-2.6	0.0	-5.7	-2.1	-1.8	-8.5	-3.2	-2.3	0.0	-1.9	-4.9	-2.6	-1.7	0.0	0.0	-1.1	-3.3
13	-0.7	-0.8	0.0	-0.7	0.0	-1.1	-0.4	0.0	-1.4	-0.7	0.0	0.0	-0.6	-0.8	-0.8	-0.6	0.0	0.0	0.0
14	-0.8	-0.9	0.0	-0.9	0.0	-1.0	-0.6	0.0	-1.3	-1.0	0.0	0.0	-0.5	-0.9	-0.8	-0.4	0.0	0.0	0.0
15	-1.4	-1.0	0.0	-1.5	-2.1	-1.2	-0.6	0.0	-0.6	-1.3	0.0	-0.5	-0.7	-1.3	-0.9	-0.7	0.0	0.0	-0.9
16	-2.9	-5.3	0.0	-2.9	0.0	-1.6	-1.0	0.0	-0.7	0.0	0.0	-1.0	-1.1	-1.5	-1.3	-3.2	0.0	0.0	-1.2
17	0.0	0.0	0.0	0.0	0.0	-1.4	0.0	0.0	-0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.4
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source: Pleven et al. (2011)

Table A2.8. CARB land use emissions factors for forest-to-pasture (Mg CO_2 $ha^{-1}y^{-1}$)

AEZ/Region	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.0	0.0	8.6	0.0	0.0	0.0	9.4	8.7	10.9	0.0	0.0	0.0	9.8	0.0	0.0	0.0	13.9	14.2	12.7
2	0.0	0.0	8.2	0.0	0.0	0.0	11.8	10.8	15.2	0.0	0.0	0.0	6.5	0.0	0.0	0.0	14.9	18.8	12.9
3	0.0	0.0	15.1	0.0	0.0	0.0	18.4	17.3	13.4	0.0	0.0	0.0	16.9	0.0	0.0	0.0	13.9	17.4	22.2
4	0.0	2.8	21.1	0.0	0.0	0.0	23.3	20.7	17.5	17.1	29.7	25.7	18.9	0.0	0.0	0.0	15.5	18.7	25.3
5	0.0	0.0	28.0	0.0	0.0	24.3	24.8	22.6	20.3	17.0	28.0	26.7	22.8	0.0	0.0	0.0	0.0	25.4	23.4
6	0.0	0.0	30.6	0.0	0.0	23.4	28.5	27.2	25.2	18.3	33.5	26.9	23.2	0.0	0.0	0.0	0.0	31.6	22.2
7	13.0	0.0	0.0	10.4	0.0	9.2	7.1	17.4	8.9	7.1	0.0	0.0	10.5	10.1	14.2	0.0	17.1	19.0	14.8
8	16.1	8.2	0.0	11.1	0.0	10.3	11.0	17.8	9.0	8.4	0.0	0.0	14.9	10.7	17.3	0.0	15.5	18.2	15.2
9	17.8	9.8	0.0	11.5	15.6	8.8	18.5	16.7	10.6	7.7	0.0	0.0	16.8	10.8	11.8	8.8	13.7	18.2	15.1
10	21.1	8.1	13.6	17.4	14.8	7.7	20.2	11.5	13.8	6.5	0.0	20.7	23.8	9.5	7.2	9.0	14.4	16.9	18.5
11	21.3	10.1	11.2	16.8	16.0	17.4	29.3	13.4	13.8	12.1	0.0	25.8	29.8	9.9	7.7	11.5	0.0	17.5	19.0
12	15.7	10.7	14.0	0.0	16.8	22.7	34.1	17.4	14.8	21.1	0.0	27.2	31.9	11.3	12.0	0.0	0.0	19.3	21.1
13	16.1	8.6	0.0	9.6	0.0	21.5	27.0	0.0	12.8	9.5	0.0	0.0	21.8	10.3	9.2	12.4	0.0	0.0	0.0
14	17.5	7.9	0.0	9.2	0.0	22.0	20.3	0.0	14.6	9.6	0.0	0.0	21.7	11.5	10.6	8.2	0.0	0.0	0.0
15	22.5	9.1	0.0	11.4	12.5	24.1	23.4	0.0	13.6	10.2	0.0	26.0	27.5	12.0	10.8	9.5	0.0	0.0	16.5
16	31.8	12.7	0.0	14.2	0.0	25.7	27.5	0.0	16.4	0.0	0.0	32.4	30.7	14.8	15.6	11.9	0.0	0.0	19.9
17	0.0	0.0	0.0	0.0	0.0	26.2	0.0	0.0	17.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.9
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source: Pleven et al. (2011)

Table A3.1. TEM land use emissions factors under base case assumptions for forest-to-cropland ($Mg\ CO_2\ ha^{-1}y^{-1}$)

AEZ/Region	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.0	0.0	4.6	0.0	0.0	0.0	2.0	1.9	6.8	0.0	0.0	0.0	1.0	0.0	0.0	0.0	9.9	3.0	3.0
2	0.0	0.0	5.7	0.0	0.0	0.0	4.4	4.1	6.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.9	5.3	4.4
3	0.0	0.0	7.3	0.0	0.0	0.0	11.8	9.0	9.9	0.0	0.0	0.0	16.5	0.0	0.0	0.0	9.9	11.6	18.5
4	0.0	0.0	17.7	0.0	0.0	27.7	18.6	18.3	16.7	0.0	29.1	27.2	23.8	0.0	0.0	0.0	9.9	21.1	21.5
5	0.0	0.0	30.6	0.0	0.0	26.1	28.5	24.5	27.7	0.0	35.4	30.0	28.0	0.0	0.0	0.0	0.0	28.2	30.9
6	0.0	0.0	31.3	0.0	0.0	25.7	29.3	31.7	33.2	0.0	35.2	32.2	32.7	0.0	0.0	0.0	0.0	30.2	34.6
7	10.6	0.0	0.0	0.0	0.0	2.1	2.3	6.3	5.7	0.0	0.0	0.0	1.5	0.0	2.6	0.0	1.8	0.0	5.1
8	12.2	0.0	0.0	13.6	0.0	8.5	4.9	8.1	7.3	0.0	0.0	0.0	3.1	18.6	3.9	0.0	6.1	8.3	5.8
9	15.5	15.2	0.0	18.1	22.5	16.4	11.5	9.6	7.9	25.1	0.0	0.0	0.0	20.1	17.2	0.0	6.1	8.4	6.7
10	19.4	17.5	21.9	16.9	22.5	20.7	20.1	15.3	11.7	25.1	0.0	27.2	20.3	19.4	20.4	13.6	6.1	13.1	11.3
11	27.4	19.7	0.0	16.9	19.4	27.4	28.8	15.3	14.4	27.1	0.0	30.0	20.3	18.2	19.9	0.0	0.0	10.5	17.6
12	28.7	20.7	22.3	0.0	20.8	20.8	25.3	15.3	19.4	0.0	0.0	32.2	0.0	0.0	32.6	0.0	0.0	10.5	25.8
13	11.5	0.0	0.0	11.3	0.0	20.8	0.0	0.0	19.4	0.0	0.0	0.0	0.0	7.4	13.1	0.0	0.0	0.0	0.0
14	11.2	6.9	0.0	9.6	0.0	20.1	0.0	0.0	19.4	26.2	0.0	0.0	0.0	9.7	13.1	8.6	0.0	0.0	0.0
15	10.0	14.7	0.0	16.5	20.9	20.1	0.0	0.0	27.2	26.2	0.0	27.2	0.0	16.2	13.1	16.1	0.0	0.0	11.3
16	22.9	13.9	0.0	25.0	0.0	20.1	0.0	0.0	24.8	0.0	0.0	30.0	0.0	19.5	13.1	16.1	0.0	0.0	17.6
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.8
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source: Zhuang et al. (2009) and authors assumptions.

Table A3.2. TEM land use emissions factors under base case assumptions for pasture-to-cropland ($Mg\ CO_2\ ha^{-1} y^{-1}$)

AEZ/Region	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.0	0.0	12.8	0.0	0.0	0.0	3.8	1.7	9.7	0.0	0.0	0.0	1.6	0.0	0.0	0.0	0.7	1.4	1.6
2	0.0	0.0	12.8	0.0	0.0	0.0	2.6	1.7	9.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8	2.1	3.0
3	0.0	0.0	6.7	0.0	0.0	0.0	5.5	1.7	2.5	0.0	0.0	0.0	1.6	0.0	0.0	0.0	1.4	4.7	6.4
4	0.0	6.9	11.3	0.0	0.0	3.1	3.8	9.6	9.7	0.0	16.9	13.8	1.6	0.0	0.0	0.0	3.6	9.5	10.9
5	0.0	0.0	15.3	0.0	0.0	3.1	3.8	3.1	14.9	0.0	16.9	15.1	1.6	0.0	0.0	0.0	0.0	12.7	15.9
6	0.0	0.0	13.9	0.0	0.0	17.3	3.8	1.7	16.4	0.0	16.9	14.0	1.6	0.0	0.0	0.0	0.0	15.4	14.6
7	1.8	0.0	0.0	1.7	0.0	1.4	3.8	1.3	1.5	8.1	0.0	0.0	1.1	1.3	2.6	0.0	0.9	2.2	2.2
8	1.8	2.1	0.0	3.7	0.0	2.6	2.6	2.1	3.1	8.1	0.0	0.0	1.8	2.6	2.7	0.0	1.6	2.6	4.8
9	2.6	6.1	0.0	8.5	8.1	11.5	4.1	1.4	3.2	8.1	0.0	0.0	1.6	7.8	3.2	0.0	2.4	4.8	6.3
10	7.9	7.5	9.9	10.6	8.1	10.7	3.8	1.7	4.0	8.1	0.0	14.5	2.6	7.7	8.6	5.7	4.7	11.1	7.9
11	11.3	9.0	12.8	4.0	8.1	3.8	3.8	1.7	5.8	8.1	0.0	14.5	3.6	5.2	10.0	0.0	0.0	12.0	8.0
12	5.8	15.4	7.8	0.0	8.1	3.1	3.8	1.7	6.5	0.0	0.0	14.5	1.6	0.0	2.3	0.0	0.0	5.7	12.6
13	4.2	6.9	0.0	3.2	0.0	3.8	3.8	0.0	13.1	8.1	0.0	0.0	1.6	5.1	1.6	0.0	0.0	0.0	0.0
14	6.2	5.7	0.0	4.8	0.0	4.9	3.8	0.0	12.9	8.1	0.0	0.0	1.6	5.3	4.3	5.5	0.0	0.0	0.0
15	7.6	6.2	0.0	9.4	8.1	8.7	3.8	0.0	9.7	8.1	0.0	14.5	1.6	8.3	2.3	7.9	0.0	0.0	3.8
16	4.3	6.9	0.0	10.8	0.0	3.1	3.8	0.0	9.7	0.0	0.0	14.5	1.6	5.2	2.3	5.7	0.0	0.0	3.8
17	0.0	0.0	0.0	0.0	0.0	3.1	0.0	0.0	9.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source: Zhuang et al. (2009) and authors assumptions.

Table A3.3. TEM land use emissions factors under base case assumptions for cropland pasture-to-cropland ($Mg\ CO_2\ ha^{-1}y^{-1}$)

AEZ/Region	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	0.0	0.0	6.4	0.0	0.0	0.0	1.9	0.9	4.9	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.3	0.7	0.8
2	0.0	0.0	6.4	0.0	0.0	0.0	1.3	0.9	4.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	1.0	1.5
3	0.0	0.0	3.3	0.0	0.0	0.0	2.7	0.9	1.3	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.7	2.3	3.2
4	0.0	3.4	5.6	0.0	0.0	1.5	1.9	4.8	4.8	0.0	8.4	6.9	0.8	0.0	0.0	0.0	1.8	4.7	5.4
5	0.0	0.0	7.6	0.0	0.0	1.5	1.9	1.6	7.4	0.0	8.4	7.6	0.8	0.0	0.0	0.0	0.0	6.4	7.9
6	0.0	0.0	6.9	0.0	0.0	8.6	1.9	0.9	8.2	0.0	8.4	7.0	0.8	0.0	0.0	0.0	0.0	7.7	7.3
7	0.9	0.0	0.0	0.9	0.0	0.7	1.9	0.6	0.7	4.0	0.0	0.0	0.5	0.7	1.3	0.0	0.5	1.1	1.1
8	0.9	1.1	0.0	1.8	0.0	1.3	1.3	1.0	1.6	4.0	0.0	0.0	0.9	1.3	1.3	0.0	0.8	1.3	2.4
9	1.3	3.1	0.0	4.2	4.0	5.8	2.0	0.7	1.6	4.0	0.0	0.0	0.8	3.9	1.6	0.0	1.2	2.4	3.2
10	3.9	3.8	4.9	5.3	4.0	5.3	1.9	0.9	2.0	4.0	0.0	7.3	1.3	3.8	4.3	2.8	2.3	5.5	4.0
11	5.7	4.5	6.4	2.0	4.0	1.9	1.9	0.9	2.9	4.0	0.0	7.3	1.8	2.6	5.0	0.0	0.0	6.0	4.0
12	2.9	7.7	3.9	0.0	4.0	1.5	1.9	0.9	3.2	0.0	0.0	7.3	0.8	0.0	1.2	0.0	0.0	2.8	6.3
13	2.1	3.4	0.0	1.6	0.0	1.9	1.9	0.0	6.6	4.0	0.0	0.0	0.8	2.6	0.8	0.0	0.0	0.0	0.0
14	3.1	2.9	0.0	2.4	0.0	2.4	1.9	0.0	6.5	4.0	0.0	0.0	0.8	2.7	2.2	2.8	0.0	0.0	0.0
15	3.8	3.1	0.0	4.7	4.0	4.3	1.9	0.0	4.9	4.0	0.0	7.3	0.8	4.1	1.2	3.9	0.0	0.0	1.9
16	2.1	3.4	0.0	5.4	0.0	1.5	1.9	0.0	4.9	0.0	0.0	7.3	0.8	2.6	1.2	2.8	0.0	0.0	1.9
17	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0	4.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Source: Zhuang et al. (2009) and authors assumptions.