Evaluating the land use change carbon flux and its impact on climate

Alex Matveev

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ABSTRACT

Evaluating the land use change carbon flux and its impact on climate

Alex Matveev

Carbon emissions from Land Use and Land Cover Change (LULCC) are currently about 30% of total anthropogenic CO_2 emissions. However, our ability to estimate the net effect of LULCC on atmospheric CO_2 concentrations is limited by uncertainties associated with carbon fluxes from land conversion. The current generation of climate-carbon models does not generally include LULCC dynamically in the simulations and as a result, carbon emissions from LULCC have typically been specified externally rather than simulated interactively by model. In addition, the extent of LULCC in model simulations has usually been limited to the extent of crops. In order to address these uncertainties, this research develops the land component of an intermediate-complexity coupled climate-carbon model – the University of Victoria Earth System Climate Model (UVic ESCM v.2.8). For that (1) the area of the agricultural land used to drive the model simulations was extended to include the pasture area, and (2) a dynamic 'bookkeeping' carbon accounting scheme was integrated into the UVic ESCM terrestrial component. The new scheme interactively allocates vegetation carbon displaced as a result of a specified LULCC to direct CO_2 emissions, as well as to short- and long-lived pools with varying decay timescales. This allows running transient simulations of the CO_2 emissions due to historical patterns of LULCC as well as, combined with use of the newest global datasets of crops and pastures, provides improved estimates of the net contribution of land use changes to climate.

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I wish to thank my family and friends who have stood by me since the beginning.

DEDICATION

I am forever indebted to my mother and my words can never express the heart-felt gratitude I hold for her. I dedicate all my work to the memory of her.

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CHAPTER 1. INTRODUCTION

The observed current and the potential future rates and scales of climatic changes as well as the magnitude of their influence on human and environmental systems represent a threat to human wellbeing (IPCC 2007: WG1- AR4). The development of realistic and coherent climate change mitigation and ecosystems adaptation strategies requires a solid scientific understanding of climate system dynamics and particularly the dynamics of climate-biosphere interactions. However, there are large uncertainties in these projections, notably those associated with estimates of carbon emissions from Land Use and Land Cover Changes (LULCC) (Houghton *et al.* 2004, Solomon *et al.* 2007, Denman *et al.* 2007). A large part of climate change studies contributing to such understanding has been based on numerical modelling. Despite the continued advancement in the development of global climate models, the representation of many components of the climate system and particularly LULCC remains oversimplified and requires significant improvement (Solomon *et al.* 2007, Strassmann *et al.* 2008).

1.1 Research rationale

This research aims to increase our understanding of carbon fluxes associated with LULCC, particularly the fluxes from deforestation and changes in agricultural practices. LULCC is responsible for about 30 to 40% of total anthropogenic carbon emissions since the preindustrial era (IPCC 2007: WG1- AR4:Ch.7, Solomon *et al.* 2007, Houghton 2003, Klein Goldewijk *et al.* 2007). The emissions of carbon dioxide (CO_2) and methane (CH_4) are the major contributors to the recent rapid climate change due to anthropogenic greenhouse gases (GHG) emissions (IPCC 2007: WG1- AR4: Ch.2 and 6).

Anthropogenic emissions have increased atmospheric CO_2 volume concentrations by approximately 100ppm (parts per million) since the pre-industrial era (IPCC 2007: WG1- AR4: Ch.6). This increase and the associated climate change have put unprecedented pressure on carbon sinks, which are currently offsetting a large fraction of anthropogenic carbon emissions as part of the Earth's natural carbon cycle (Houghton 2003a, Matthews 2005, Matthews *et al.* 2005a and b, Schimel 2001). Higher temperatures, associated with this climate change, will likely result in weakening of the natural carbon sinks (Canadell *et al.* 2007, Fung *et al.* 2005), especially the terrestrial carbon sink which has also been extensively altered by human activity and particularly by the LULCC.

Strassmann *et al.* (2008) have calculated that historical LULCC have already reduced the capacity of the potential (and thus expected) future carbon sink by the equivalent of 80–150Gt of additional carbon emissions by the year 2100. Additionally, many models have shown the potential for positive feedbacks in the climate-carbon cycle system to accelerate the rate of CO_2 increase in the atmosphere as natural carbon sinks are weakened in response to climate change. Given that natural (i.e. constantly present non-anthropogenic) CO_2 fluxes are tens of times larger than anthropogenic emissions, any 'minor' decrease in the absorption capacity of the terrestrial or ocean carbon sinks carries the potential to further rapidly increase CO_2 concentrations in the atmosphere.

Furthermore, the effects of LULCC have been shown to exhibit high regional variability (Feddema *et al.* 2005 a and b, Jonko *et al.* submitted) thus providing a real possibility of inducing even greater outcomes in certain regions. Many studies highlight much higher than average levels of warming, general circulation disturbance and carbon emission rates observed in the tropics and the mid-latitude regions as a result of LULCC (Betts *et al.* 2004). This implies even greater escalation of the effects of land use change on climate due to the particular sensitivity of the tropical and mid-latitude regions to climatic disturbances and also due to the amplifying capacity of the positive carbon/climate feedbacks (Gitz and Ciais 2003, Matthews 2005, Matthews *et al.* 2005a and b).

However, the amplified CO_2 emissions are only a part of the large range of the biogeophysical and the biogeochemical effects the LULCC have on climate, as well as are only a part of a large range of uncertainties associated with those effects. An additional uncertainty arises from modifications in the biogeochemistry of the biosphere associated with LULCC, specifically those linked to fertilizer applications and altered water cycle (Fung *et al.* 2005, Thornton *et al.* 2007); these modifications alter the atmospheric composition as well as the stability of the carbon cycle (Denman *et al.* 2007). The climate-carbon cycle system response to those changes still remains ambiguous. This also implies the uncertainties in the estimates of the current carbon balance in which the LULCC contribution is the most uncertain (IPCC 2007: WG1- AR4: Ch.7, Matthews *et al.* 2004). This uncertainty arises from the current model representation of LULCC which is subject to oversimplification of significant processes (e.g. changes in agricultural practices and wood product carbon accounting) as well as to omitting of significant values (e.g. pastures). Subsequently, model estimates of changes in the amount of carbon stored in the soil and terrestrial vegetation are uncertain and so are the current GHG inventories as well as the estimates of the historical LULCC emissions and the terrestrial carbon sink strength.

1.2 Research objectives

With this study I aim to improve the current terrestrial carbon inventories and estimates of the historical LULCC CO_2 emissions and, thus, strength of the terrestrial carbon sink. I aim to accomplish this objective by performing transient model simulations from the year 1700 to 2000 including the new and extended LULCC datasets and using a dynamic land use carbon accounting method. This work develops the terrestrial component of the University of Victoria Earth System Climate Model (UVic ESCM v2.8) – an intermediate-complexity coupled climate-carbon model. I introduce LULCC dynamically into the model simulations by incorporating a new carbon accounting scheme based on the bookkeeping model (Houghton 1983, Strassmann *et al.* 2008). In accordance with this new carbon accounting scheme, the vegetation carbon displaced as a result of a specified spatial change in the LULCC pattern is allocated to litter, direct CO_2 emissions, and short- and long-lived carbon pools with varying decay timescales (Matveev and Matthews 2009a, b). These timescales have been associated with the lifetime of wood products after land clearing (Strassmann *et al.* 2008). In addition to the new dynamical representation of LULCC, a new combined spatially referenced dataset of crops (Ramankutty and Foley 1999, Ramankutty *et al.*

2008) and pastures (Klein Goldewijk *et al.* 2007, Houghton 2003) have been used in the simulations allowing better estimates of the CO_2 emissions following LULCC and, thus, better estimates of the net contribution of LULCC to climate change.

1.3 Research design

The research is completed using a quasi-experimental design, which uses both multiple variables and multiple waves of measurement. This method allows a researcher to manipulate an independent variable under controlled conditions while tracking the output (dependent variable). Thus the process of interest has been followed from antecedent (preceding) to consequent conditions. The power of this design is in unambiguous identification of cause-and-effect relationships.

However, in order to affirm the cause-and-effect relationship the necessary condition is that the manipulated independent variable is the only variable affecting the dependent variable. This limitation was overcome in this work by holding the other variables that might also have an effect on the variables of interest (dependent variables) constant during the model calibration runs. The second major limitation to the quasi-experimental design is intrinsic to all model simulations and has been difficult to overcome – the research is completed in the laboratory conditions and may not entirely reflect the complexity of the real world. Nevertheless, the highly controlled procedure of the experiment allows the explicit detection of the cause-and-effect relationships thus securing validity of the results.

CHAPTER 2. CURRENT TOPICS

LULCC related emissions that directly and indirectly affect the amount of CO_2 in the atmosphere have been an important contributor to the total human impact on the climate system during the industrial era; hitherto this contribution represents a large source of uncertainties in current climate model projections (Brovkin *et al.* 2004, Canadell 2002, Claussen *et al.* 2002, Matthews *et al.* 2004, de Noblet *et al.* 2000, Strassmann *et al.* 2008). Many researchers have shown that historical and ongoing large-scale LULCC have resulted in large carbon emissions to the atmosphere, thus accelerating global warming and intensifying climate disturbance: Brovkin *et al.* (2004) and Matthews *et al.* (2004) calculated that carbon emissions from land use change may have contributed between 12 and 35 ppm of the total CO_2 increase from 1850 to 2000 (see also Table 2.0.1).

Table 2.0.1. Estimates of forest area, contribution to CO_2 increase from anthropogenic land cover change, RF due to the land use change-induced CO_2 increase and surface albedo change (relative to pre-industrial vegetation and PNV) (Source: Table 2.8 in IPCC 2007: WG1-AR4)

Land Cover Dataset	Forest Area (PNV* 10^6 km^2)	Forest Area (circa 1700 10^6 km^2)	Forest Area (circa 1990 10^6 km^2)	**Part in CO_2 raise** (1850–2000[a] ppm)	**CO_2** RF** **(W/m^2)**	**Albedo** RF vs. PNV **(W/m^2)**	**Albedo** RF vs. 1750 **(W/m^2)**
Ramankutty and Foley (1999)	55.27	52.77[b]	43.97[c]	**16[d]**	0.27	**−0.24[e]** **−0.29 to 0.02[f]** **−0.2[g]**	**−0.18[e]** **−0.22 to +0.02** **−0.14[g,i]** **−0.15 to −0.28[i,j]** **−0.075to −0.325[i,l]**
Klein Goldewijk (2001)	58.6	54.4	41.5	**12[d]**	0.20	**−0.66 to +0.1[f]**	**−0.50 to +0.08** **−0.275[i,l]**

Houghton (1983, 2003)		62.15	50.53^n	**35^d** **26^o**	0.57 0.44	n.a.	n.a.
MODIS (Schaaf et al., 2002)						**−0.09**	**−0.07**
SARB^r						**−0.11to −0.55^f**	**−0.08 to −0.41**

Notes:
* PNV - potential natural vegetation
** RF – radiative forcing

[a] The available literature simulates CO_2 rises with and without land use relative to 1850.
[b] 1750 forest area reported as 51.85 x 106 km2
[c] 1992 forest area

[d] Land use contribution CO_2 rise from Brovkin et al. (2004)

[e] Albedo RF from Betts et al. (2007). Land cover data combined from Ramankutty and Foley (1999), Klein Goldelwijk (2001)
[f] Albedo RF from Myhre and Myhre (2003). Range of estimates for each land cover data set arises from use of different albedo values
[g] Albedo RF from Brovkin et al. (2006)

[i] Estimate relative to 1700

[j] Albedo RF from Matthews et al. (2003)
[l] Albedo RF from Matthews et al. (2004)

[n] 1980 forest area
[o] Land use contribution to CO_2 rise from Matthews et al. (2004). Estimate only available relative to 1850 not 1750

[r] Surface and Atmosphere Radiation Budget; http://www-surf.larc.nasa.gov/surf/

The CO_2 RFs are for 2000 relative to 1850, calculated from the land use change contribution to the total increase in CO_2 from 1850 to 2000 simulated with both land use and fossil fuel emissions by the carbon cycle models.

Matthews *et al.* (2004) also showed that CO_2 emissions from land cover changes over the past 150 years have amplified the greenhouse warming by as much as 0.3°C on the global average. This represented over 30% of the overall simulated temperature increase in this study and corresponds to about 50% of the overall planetary temperature increase during the last century (IPCC 2007 AR4: WG1: Ch.2 and 3).

Hence, the LULCC contribution to the increased atmospheric CO_2 concentrations have significantly amplified global warming and the overall disturbance, both directly, through carbon emissions and deforestation (missed sink), and also indirectly, mainly through radiative forcings (RFs) including surface emissivity, aerodynamic roughness, latent and sensible heat fluxes. Additionally, the combination of direct and indirect effects of LULCC have significantly altered soil and vegetation carbon pools. These combined effects alter the existing global carbon balance and also introduce an additional source of uncertainties in the estimate of the net effects of LULCC on climate.

2.1 Effects of land use change on carbon fluxes

Considering multiple possible definitions of the net terrestrial carbon flux, the current use of the term and how it is linked to land use changes requires some specification. The net terrestrial carbon flux considered here is usually defined as the net ecosystem exchange or NEE (Davidson and Ackerman 1993, Saleska *et al.* 2006) and is measured as a difference between photosynthesis (or gross primary production, GPP) and respiration (both autotrophic, R_a and heterotrophic, R_h), as well as the changes in biomass and soil carbon pools due to human and natural disturbances. Subsequently, depending on the value of each term, the NEE can acquire either positive or negative values thus corresponding to a net carbon source or sink respectively:

$$\text{NEE} = \text{GPP} - R_a - R_h - \text{Disturbance}.$$

The productivity terms also include intermediate divisions such as net primary production (NPP) and net ecosystem production (NEP, a.k.a. net biome production NBP) (see also Figure 2.1.1), where:

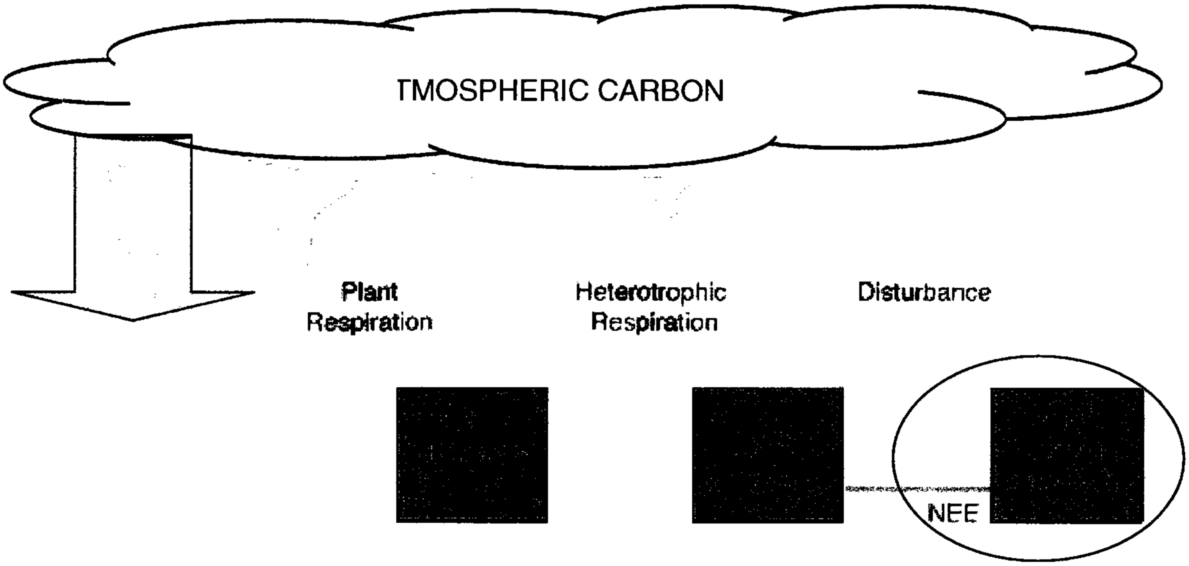


Figure 2.1.1. Scheme of carbon exchange between the land surface and the atmosphere (Modified from Gruber 2008)

$$\text{NPP} = \text{GPP} - R_a,$$

$$\text{NEP} = \text{NPP} - R_h, \text{ and}$$

$$\text{NEE} = \text{NEP} - \text{Disturbance} = \text{NPP} - R_h - \text{Disturbance}.$$

Although the Disturbance term includes both anthropogenically driven and naturally occurring processes, a significant part of these natural disturbances has also been amplified by or has been due to human-induced LULCC (Raffa *et al.* 2008).

Table 2.1.1. Spatial and temporal scales of different effects of land use on climate and po sible pathways (Source: Torn 2008 and IPCC 2007: WG1-AR4)

Efflux or surface property	**Lifetime**	**Spatial Scale**	**Climate Influence** (Radiative Forcing, RF)
CO_2	3 – 200-10000y	Global	RF(W/m^2), GWP^b = 1
N_2O	114 y	Global	RF(W/m^2), GWP^b = 310
CH_4	1 - 12 y	Global	RF(W/m^2), GWP^b = 21
H_2O^{vapour}, ET^a/Sensible Heat	~10 days	Local - Reg.	Temperature, PBL^c, Precipitation, RF(W/m^2),
Aerosols	Days-weeks	Regional/Cont	Cloud condensation nuclei, RF(W/m^2)
Ozone	Days-weeks	Local-Regional	RF(W/m^2),
Albedo	vegetation	Local	RF(W/m^2),
Roughness	vegetation + geological	Local	Turbulent heat transfer, ET^a

[a] ET - evapotranspiration

[b] GWP - global warming potential; GWP depends on the efficiency of the molecule as a GHG and its atmospheric lifetime; measured as mass equivalent to that of CO_2

[c] PBL - the planetary-boundary-layer; the role of PBL in the Earth system is the atmosphere-land/ocean/biosphere coupling module determining:

- the resistance and heat/mass transfer
- the near-surface turbulent fluxes
- the fluxes at the PBL outer boundary(the entrainment)
- turbulence closures

Largely, this amplification has been associated with the effects that LULCC have on surface exchange of other GHGs, energy, moisture and momentum (all these in addition to the direct effects on carbon fluxes) (Cooley *et al.* 2005, Torn *et al.* 2008, see also Table 2.1.1).

The effects of land use change on carbon fluxes are generally organized into two major subgroups: biogeophysical effects and biogeochemical effects. Subsequently, the biogeophysical subgroup includes the large-scale surface alterations, including modified surface aerodynamic roughness that affects general circulation patterns as well as surface albedo changes. The surface emissivity and moisture fluxes have been affected through evaporation and transpiration, as well as latent and sensible heat fluxes and the ratio of latent to sensible heat – the Bowen ratio. These effects have also shown to exhibit regional and latitudinal variability, as well as to represent a source of uncertainty (Feddema *et al.* 2005 a, Jonko *et al.* submitted, Betts 2001). For example, the surface albedo changes attributed to LULCC may have a dominant influence on climate of mid- and high-latitudes (Betts *et al.* 2004). The radiative forcing (RF) due to surface albedo change is estimated as $-0.2W/m^2 \pm 0.2W/m^2$ on average (Betts 2001, Bounoua *et al.* 2002). The surface energy balance has also been modified through human induced changes in water cycle (e.g. irrigation). These effects, in turn, through modified radiation and energy balances will affect surface temperature, convective patterns and thus, through turbulent transfer of heat and moisture, water vapour exchange between the land and the atmosphere (Claussen *et al.* 2001, DeFries *et al.* 2002, Feddema *et al.* 2005b, Matthews *et al.* 2005a).

Alternatively, biogeochemical effects include modified land biomass, leaf area, moisture and energy balances, which each and jointly affect biogeochemical cycles as well as terrestrial carbon, water and nutrient budgets. Although the current research directly focuses on the biogeochemical component of LULCC, the related biogeophysical processes are also taken into account as they are an intrinsic part of the UVic ESCM simulations. Some of these processes, such as nutrients cycling, fertilization and the associated feedbacks to the carbon cycle are not yet fully incorporated to the UVic ESCM, which is one of the limiting factors in our simulations. Some uncertainty related to this limitation will be discussed in the subsequent sections.

Overall, the most prominent effects of LULCC on climate are large global CO_2 emissions and the induced changes in the capacity of the terrestrial carbon sink. The global net flux of carbon from the land converted by humans from its natural state to some other state for the period 1850 - 2000 is estimated as approximately 150 gigatonnes of carbon (GtC = 10^{15}g of carbon, see also Table 5.0.1F for reference) (Houghton 2008). In addition, LULCC is estimated to have decreased the capacity of the terrestrial carbon sink by 113Gt C between 1850 and 2000 (Strassmann *et al.* 2008).

Table 2.1.2. Global land cover in 1990, and land- use changes between 1990 and 2050, and 2050 and 2100 (in 10^6 ha) and ranges for the four SRES scenarios (Source: Table 4-17 in SRES 2000)

Type		**Land Area** (10^6 ha)	**Land-Use Change (million ha)**							
		1990	**1990-2050**				**1990-2100**			
			A1[a]	**A2**[b]	**B1**[a]	**B2**[c]	**A1**[a]	**A2**[b]	**B1**[a]	**B2**[c]
Cropland		**1434-1472**	-17	n. a.	-7	167	-39	n. a.	325	-394
	min		-113	-187	-305	-49	-826	-422	-979	-582

	max		**+904**	**+267**	**+461**	**+628**	**-39**	**+420**	**-30**	**+325**
Grassland		**3209-3435**	109	n. a.	-650	155	188	n. a.	-1537	307
	min		-794	+194	- 650	- 491	-1087	+313	-1537	-491
	max		**+1714**	**+1218**	**+1335**	**+1331**	**+622**	**+1262**	**+320**	**+823**
Energy Biomass		**0- 8**	418	n. a.	263	288	495	n. a.	196	307
	min		+12	+18	0	0	+ 3	+ 67	0	+ 4
	max		**+745**	**+311**	**+260**	**+288**	**+1932**	**+396**	**+1095**	**+597**
Forests		**4138-4296**	-106	n. a.	274	57	-92	n. a.	1260	227
	min		**-1146**	**- 778**	**- 667**	**- 732**	**- 464**	**- 673**	**+274**	**- 116**
	max		+175	+302	+274	+57	+480	-19	1266	+227
Others		**3805-4310**	-405	n. a.	122	-667	-552	n. a.	482	-1166
	min		**-1072**	**-833**	**-579**	**-667**	**- 873**	**-1085**	**-983**	**-1166**
	max		+15	-431	+122	-98)	+566	-278	-482	-137

Notes:

Estimates for the four SRES marker scenarios and ranges (minimum and maximum) based on different model representations of related processes. Appropriate land-use change and emission scenarios calculated with alternative models with consistent socio-economic driving-

force assumptions.
[a] AIM and IMAGE (A1 and B1 markers, respectively) model both land- use changes and related emissions.
[b] ASF (A2 marker) models changes in carbon fluxes only, whereas
[c] MESSAGE (B2 marker) does not include a land- use change and related GHG emissions module.

These estimates are largely due to the expansion of croplands and pastures that currently cover about 40% of the productive land surface (Klein Goldevijk, 2001, see also Fig .1 and Appendix A) and this extent may substantially increase over the current century (SRES 2000, see also Table 2.1.2 and Figure 3.2.2B).

Hurtt *et al.* (2006) estimate the overall current human impact has modified 42 to 68% of the total land surface. They also show that some lands have undergone multiple land use transitions since the preindustrial state because of shifting cultivation, temporary or permanent abandonment/relocation of agricultural lands and cropland-pasture rotations. Both harvested/regrown biomass and cultivated/abandoned soil play a part in the carbon release and uptake, but the estimates of their magnitude and even sign remain vague (Arora and Matthews 2009, Portner *et al.* 2009). These main constituents of the LULCC/carbon cycle/climate system interactions and the uncertainties, associated with their modelling and future projections, are the focus of this work.

2.2 Soil carbon stocks and land use change

Soil carbon stocks are considered among the most important and also among the most uncertain contributors to carbon fluxes from LULCC (IPCC AR4

2007). Each soil type has an equilibrium carbon content which depends on the type of growing vegetation, on a particular soil biogeochemical composition and on the soil moisture balance and temperature regime (Allen 1985). The equilibrium here means that the soil carbon pool has balanced its inward and outward carbon flows which, if altered by LULCC, will tend to move towards a new equilibrium thus turning the affected soil patch into a carbon sink or a carbon source for the period until this new equilibrium state is reached. Evidently the magnitude of this carbon sink or source will, first and foremost, depend on the spatial extent of the affected soil that, subsequently, in most part defines the size of the disturbed carbon pool. At present the extent of soil carbon stocks' alterations attributed to LULCC is very large and represents a significant contribution to carbon in the atmosphere (Denman *et al.* 2007, Guo and Gifford 2002).

Table 2.2.1. Estimates of terrestrial carbon stocks (global aggregated values by biome), Source: House et al. 2002

Biome	**Area (10^9 ha)**		Global Carbon Stocks (PgC)[d]					
	WBGU[a]	RSM[b]	**WBGU[a]**			**RSM[b] IGBP[c]**		
			Plants	**Soil[d]**	**Total**	**Plants**	**Soil[d]**	**Total**
Tropical forests	1.76	1.75	212	216	428	340	213	553
Temperate forests	1.04	1.04	59	100	159	139[e]	153	292
Boreal forests	1.37	1.37	88[f]	471	559	57	338	395
Tropical savannas & grasslands	2.25	2.76	66	264	330	79	247	326
Temperate grasslands & shrubs	1.25	1.78	9	295	304	23	176	199

Tundra	0.95	0.56	6	121	127	2	115	117
Deserts and semi deserts	4.55[h]	2.77	8	191	199	10	159	169
Croplands	1.6	1.35	3	128	131	4	165	169
Wetlands[g]	0.35	–	15	225	240	–	–	–
Total	15.12	14.93[h]	466	2011	2477	654	1567	2221

[a] WBGU (1998): forest data from Dixon *et al.* (1994); other data from Atjay *et al.* (1979)

[b] RSM: Roy, Saugier & Mooney (RSM) 2001. Temperate grassland and mediterranean shrubland categories combined

[c] IGBP-DIS (International Geosphere–Biosphere Programme – Data and Information System) soil carbon layer (Carter & Scholes, 2000) overlaid with DeFries *et al.,* 1995) current vegetation map to give average ecosystem soil carbon

[d] Soil carbon values are for the top 1 m, although stores are also high below this depth in peatlands and tropical forests

[e] RSM temperate forest estimate is likely to be too high, being based on mature stand density

[f] WBGU boreal forest vegetation estimate is likely to be too high due to high Russian forest density estimates including standing dead biomass

[g] Variations in classification of ecosystems can lead to inconsistencies. In particular, wetlands are not recognized in the RSM classification

[h] Total land area of 14.93 x 109 in RSM includes 1.55 x 109 ha ice cover not listed in this table. In WBGU, ice is included in deserts and semidesterts category.

Sauerbeck (2001) estimates the release of soil and biomass carbon into the atmosphere due to agriculture to be about 170GtC since the preindustrial era with about a 42Gt contribution from soil carbon, and the current cumulative release from land clearing in the tropics to be about 1.2Gt of carbon yearly.

A comprehensive meta-analysis of the effects of the LULCC on soil carbon stocks was completed by Guo and Gifford (2002). They quantified variances in soil carbon stock modification between the prevalent types of vegetation cover transitions and, consequently, highlighted the importance of accounting for the nature of the vegetation cover transition in carbon accounting schemes as different transitions may have widely divergent effects on soil carbon stocks. Indeed, on the global average land conversion is responsible for at least a 9% loss of carbon in soil stocks (Guo and Gifford 2002). However, the particular types of land cover transitions may invoke a change ranging from a 42 to 59% loss of soil carbon for native forest to crop or pasture to crop types of transitions, to a gain of up to 53% for crop to secondary forest transitions (see also Table 2.2.2).

Table 2.2.2. Soil carbon response to various land use conversions (prevalent types are in bold) Source: Guo and Gifford 2002.

Type of conversion	**Number of observations**	**Soil carbon change (%)**	**95% confidence interval**	
			From	To
Forest to Pasture	170	+8	+5	+10
Pasture to Secondary Forest	6	-18	-40	+8
Pasture to Plantation	83	-10	-13	-4
Forest to Plantation	30	-13	-3	-19
Forest to Crop	37	**-42**	-51	-36
Crop to Plantation	29	+18	+14	+24
Crop to Secondary Forest	9	**+55**	+39	+72
Pasture to Crop	97	**-59**	-65	-55
Crop to Pasture	76	**+19**	+15	+25
Overall	537	-9	-11	-8

However, many of those transition type estimates are site scale observations which are not yet fully generalized and, consequently, are not yet incorporated in the current generation of climate models. Subsequently, the type of vegetation cover transition is often omitted in model simulations which is a limitation and another source of uncertainty inherent to a great majority of models.

In addition to the direct carbon exchange with the atmosphere due to modified soil carbon stocks, their ongoing modification under LULCC significantly alters the global carbon cycle and thus also amplifies the carbon cycle/climate feedbacks. For the most part these feedbacks are positive and may represent a significant additional source of carbon in the atmosphere and definitely represent an additional source of uncertainty in climate modeling (Matthews 2005). Generally, these effects are only partially taken into account in the current generation of coupled climate-carbon models.

2.3 Uncertainties associated with carbon fluxes from LULCC

Uncertainties associated with carbon fluxes from LULCC include both value and structural uncertainties (IPCC 2007: AR4). The value uncertainties here generally arise from scarcity and disagreement of global data, especially historical data; the structural uncertainties, with regard to the LULCC modeling, arise from divergent and often incomplete, omitted, or oversimplified model representations of LULCC processes. These uncertainties result in a large discrepancy in climate model outputs that leads to uncertainties in estimates of future atmospheric CO_2 concentrations, of the global carbon budget and of the net

LULCC effect on the global carbon cycle (Denman et al. 2007, Houghton et al. 2004, Pacala *et al.* 2001, Prentice et al. 2001).

Differences in estimates of the LULCC effects may also result from different assessment methods rather than from model uncertainties or data limitations. Indeed, current methods to estimate the net land biosphere exchange include bottom up methods (inventories, eddy-flux covariance) and top down (atmospheric CO_2 inversion) methods (Houghton 2003a). Different methods can inherently include or omit different parts of the carbon/climate interactions, as do, for example, these top-down (atmospheric based) and bottom-up (forest biomass and LULCC based) approaches. At large scales the top-down approach may be appropriate as it incorporates climate, soil, and biome-specific factors. However, the land use history, the spatially explicit patterns and other processes where average statistics do not capture system behaviour are largely omitted by this method. Some uncertainty also arises from use of different methods even if the similar general approaches (i.e. top-down or bottom-up) have been used. Generally, methods based on the soil carbon stock estimates (bottom-up inventories) tend to overestimate source (and thus CO_2 emissions) and underestimate sinks of atmospheric carbon (Stephens *et al.* 2007, Saleska *et al.* 2006). Methods based on the eddy covariance method (bottom-up eddy flux) may underestimate carbon emissions and overestimate stocks (Stephens *et al.* 2007). Gurney et al. (2004) using the top–down method of inversion of simulated tracer transport, estimated a northern mid-latitude carbon exchange of -2.4 ± 1.1GtC/yr (net sink) and the tropical carbon exchange of 1.8 ± 1.7GtC/yr (net source). By contrast, Stephens *et al.* (2007) while using improved methods of measuring spatial and temporal vertical atmospheric CO_2 distributions (also a top-down approach) observed significantly weaker than previously estimated annual-mean vertical CO_2 gradients. Subsequently, their research estimated a northern mid-latitudes carbon sink of -1.5 ± 0.6GtC/yr and a tropical source of +0.1 ± 0.8GtC/yr that is notably smaller than the earlier estimates.

Ramankutty *et al.* (2007) points to the uncertainties associated with land-cover dynamics following deforestation, including harvesting of secondary vegetation, the decay of product and slash pools, and the fluxes from regrowing forest. The paper also shows the importance of estimating historical land-cover changes for accurate carbon-flux estimates as well as estimating the sensitivity of carbon fluxes to estimates of the partitioning of cleared carbon into instantaneous burning vs. long-timescale slash pools (bookkeeping method).

Some uncertainties are also associated with the use of 'bookkeeping method' to estimate LULCC emissions (Houghton *et al.* 1983). The method redistributes the carbon liberated during the transformation of natural land into cropland between the soil and the atmosphere carbon pools. The method also takes into account temporal variance between the carbon release and its uptake by the atmosphere. Leemans et al. (2002) noted that if a carbon-only model is used the method neglects CO_2 - climate - carbon cycle feedbacks. These feedbacks incorporate a negative loop due to ocean and terrestrial carbon uptake increasing with the increase of atmospheric CO_2 concentrations, and a positive feedback loop from weakened carbon sinks due to accelerated soil carbon decomposition under climate change, decreased tropical vegetation productivity, the effect of climate warming on ocean carbon solubility and circulation, and on ocean biological productivity. However, in coupled carbon-climate models, such as the UVic ESCM, these feedbacks are incorporated naturally, and consequently, the bookkeeping approach may be efficiently used.

CHAPTER 3. METHODS

In this work I use the version 2.8 of the UVic ESCM to run a series of transient simulations, incorporating CO_2 emissions following specified spatial patterns of LULCC, to estimate the net historical contribution of the LULCC to atmospheric CO_2 concentrations and, thus, to climate change. These simulations are based on the recent spatially explicit historical land use datasets of crops and pastures. The original version 2.8 of the UVic ESCM has been modified in order to incorporate a bookkeeping carbon accounting scheme into its terrestrial component that tracks the LULCC induced changes in carbon content of the affected biomass and soil carbon pools.

3.1 Modelling approach

The terrestrial model of the UVic ESCM simulates the areal competition of five major Plant Functional Types (PFTs) in response to climatic conditions and tracks the associated carbon changes in the affected vegetation and soil carbon stocks. The original carbon allocation scheme was enhanced in order to accommodate the effects of LULCC on vegetation and soil carbon pools. According to the new carbon accounting scheme the vegetation carbon, displaced as a result of a specified land cover change, is interactively allocated to the soil pool, to direct CO_2 emissions, as well as to short- and long-lived wood product (intermediate) carbon pools with varying decay timescales. Sections 3.1 and 3.2 will describe the assumptions used in the current model setup, the boundary conditions used to drive the simulations, the data used to drive these simulations and the adjustments made to the original datasets to be used in the UVic ESCM v2.8.

Section 3.3 describes the model and the modifications made to the original version of the model in order to complete the estimates of LULCC carbon emissions over the last 300 years. Section 3.4 provides the details of the completed series of model simulations including the details of the transient runs as well as the details of the UVic ESCM calibration and validation. The results obtained from these simulations and their implications are presented in the Chapter 4 and the following Conclusion.

3.1.1 Carbon flux from land conversion

As was noted in section 2.2, the net carbon flux from land conversion is highly sensitive to the type of vegetation cover transition because each transition type induces significantly different changes in soil carbon pool (for reference see Table 2.2.2 on p.16). It was also noted that at present the transition types are usually not included in global climate models. Although in the current model experiment this information is also not included explicitly in simulations, the way the vegetation cover is simulated in the terrestrial module of the UVic ESCM helps to partially avoid the above source of uncertainty. This is because the native forest to crop transition, which is the prevalent type of transition associated with the LULCC, is in certain way inherent to all dynamic vegetation model schemes, as long as the naturally grown forest and the crops are both restricted to major PFTs, which include broadleaf trees, needleleaf trees, shrubs and grasses. The current version of UVic ESCM uses a Dynamic Global Vegetation Model (DGVM) named TRIFFID (Top-down Representation of Interactive Foliage and Flora Including Dynamics) as a part of its terrestrial component which defines the state of land surface vegetation in terms of the soil carbon balance and the areal coverage, the leaf area index (LAI), and the canopy height calculated for five PFTs (Cox *et al.* 1999, Cox 2001). Thus, for the type of the vegetation cover transition in which we are most interested, the soil carbon stock modifications are inherently accounted for in the current version of the UVic ESCM. However, for the future research involving the land cover transitions within the UVic ESCM, the terrestrial part of the model should include the explicit model description of land cover transitions and possibly describe separate crops and the associated rotations in the context of a separate crop model coupled to the GCM.

Some uncertainty arises here from the significant difference between natural types of vegetation (PFTs inherent to all DGVMs) and crop types (planted and harvested on a regular basis). Additional uncertainty arises from the large asymmetry between the soil carbon responses to crop–pasture and pasture–crop, as well as forest–crop and crop–forest transitions (Guo and Gifford 2002, see also Table 2.2.2 on p.16). The reason for this uncertainty is that the model will represent plantation as naturally grown secondary forest, unless prescribed otherwise, should favourable climatic conditions happen in the available grid cell (or a grid cell fraction which is free from other PFTs). Similarly, both crops and pastures are treated as naturally grown grasses. This may lead to an overestimate of a potential soil carbon accumulation of up to 40% of total grid cell soil carbon content (Guo and Gifford 2002, Post and Kwon 2000). This also will imply an additional uncertainty in the estimates of the net effect of the LULCC to climate ranging from 20 to 60% per each areal difference between plantations and naturally regrown secondary forest land (Table 2.2.2).

3.1.2 Bookkeeping approach

In order to improve the representation of LULCC in the UVic ESCM I have incorporated a more sophisticated carbon accounting scheme in the land part of UVic ESCM. This scheme is based on the bookkeeping approach (Houghton 1983, 2003, Strassmann *et al.* 2008) though it differs from those described in the literature in a number of ways. In particular, in the developed scheme I have overcome a number of limitations previously inherent to this approach.

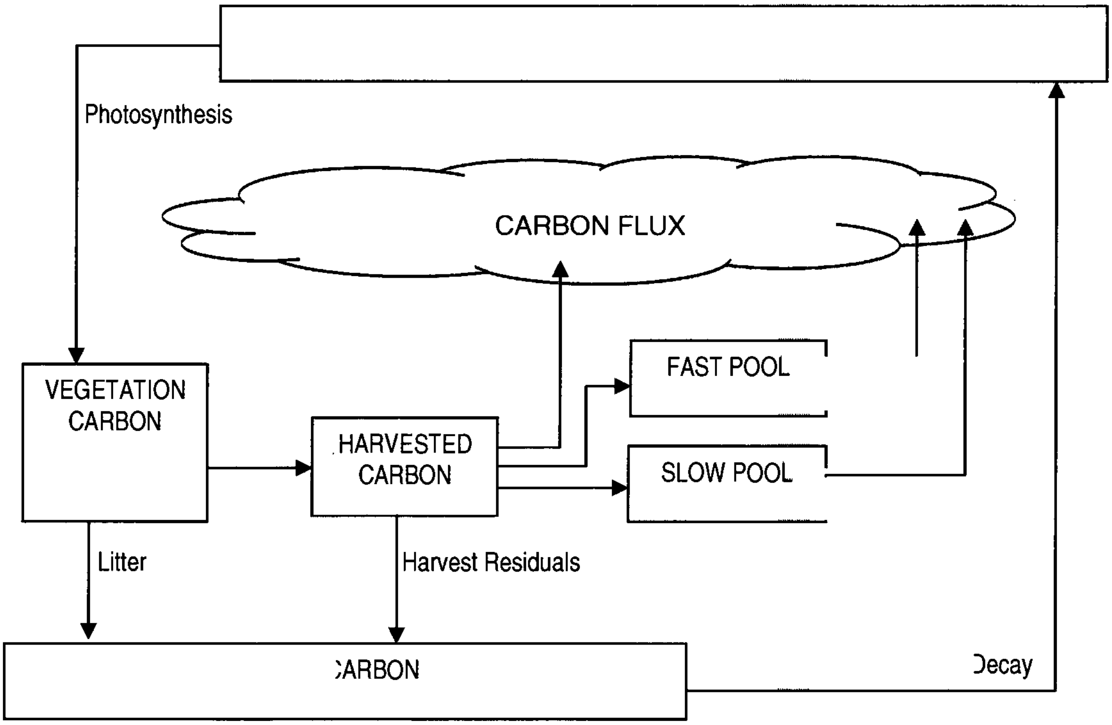


Figure 3.1.1. Scheme of the LULCC carbon allocation linked to the soil component and the DGVM TRIFFID in the modified version of the UVic ESCM v.2.8

The major deficiency attributed to the bookkeeping method has been described in Leemans *et al.* (2002) and Strassmann *et al.* (2008) which noted that the method often neglects the feedbacks to atmospheric CO_2 concentrations and climate associated with LULCC. This problem was resolved in this work by linking the bookkeeping carbon accounting scheme, used in the simulations, to a coupled climate – carbon model. Figure 3.1.1 shows the outline I used to integrate the intermediate carbon pools into the UVic ESCM v. 2.8 for this model experiment. As can be seen from the sketch the carbon accounting scheme is dynamically connected to the terrestrial part of the carbon cycle in the GCM. Subsequently, the feedbacks associated with the effect of rising atmospheric CO_2 on photosynthesis will be accounted for in the each consecutive model time step (Fig 3.1.1). Likewise, the vegetation expansion will also be dynamically adjusted should the climatic conditions change in the affected grid box.

Another uncertainty often attributed to earlier attempts of using the bookkeeping approach in coupled climate models arises if LULCC fluxes are prescribed externally (Leemans *et al.* 2002, Strassmann *et al.* 2008), rather than calculated by the model (i.e. if they are exogenously specified in the way similar to that of fossil fuel emissions). Gitz and Ciais (2004) and Strassmann *et al.* (2008) have noted that terrestrial carbon stocks are usually overestimated in such simulations, because cultivated land has faster carbon turnover and reduced sink capacity, by comparison to that of forested land, but its growing areal extent is not included dynamically in the model simulations. This problem is avoided in the current study, since here the model calculates the carbon flux from land conversion dynamically in its terrestrial component based on a specified spatial extent of agricultural land. In addition, in this model experiment I have improved on previous simulations of historical LULCC by including not only a cropland dataset but also a pastures dataset based on Klein Goldewijk (2001), and Klein Goldewijk *et al.* (2007).

3.2 Land use Data

Overall, in this work I have compiled four different datasets of crops and pastures in a continuous gridded series of 300 years of LULCC data. I then used this data to drive a series of transient simulations with the UVic ESCM. Both crops and pastures are represented in the UVic ESCM v. 2.8 as a mixture of C3/C4 natural grass PFTs, where their ratio in each grid cell depends solely on the simulated climatic envelope for that grid box, and the spatial extent of agricultural land is restricted to the specified land use area. This also ensures that the agricultural part of the model grid is excluded from the other model PFTs competition. However, the representation of the agricultural land as naturally grown grasses has some limitations that will be discussed later in Section 4.

3.2.1 Data collection

Global historical distributions of croplands from 1700 to 1992 have been available for climate modeling since 1999 when Ramankutty and Foley (1999) reconstructed and published a geographically explicit continuous global dataset with 0.5 degree spatial and 1 year temporal resolution. They originally started from a map of permanent cropland areas for the year 1992, which were derived from satellite imagery and FAO assessment, and then derived the historical distribution of croplands from 1992 back to 1700 based on the reconstructions with a simple land cover change model and using the available historical inventories and various interpolation methods (Ramankutty and Foley 1999, Hurtt *et al.* 2006). Klein Goldewijk (2001) within the HYDE-2 (History Database of the Global Environment, version 2 - a project developed under the authority of the Netherlands Environmental Assessment Agency) has published a reconstruction of the historical pastures from 1700 to 1900 with a 0.5 degree spatial resolution and 50 years temporal resolution.

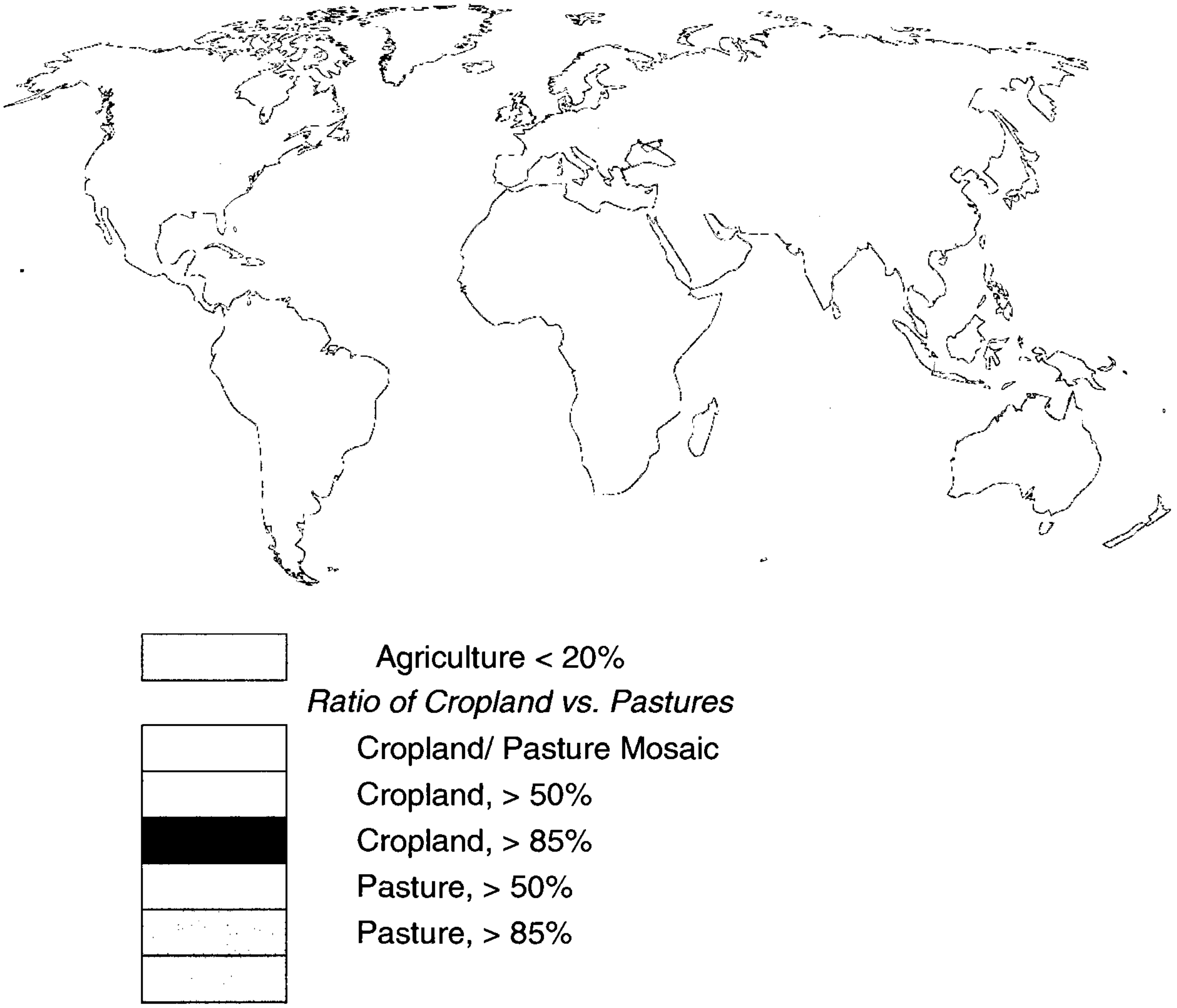


Figure 3.2.1 Current distribution of agricultural land (Sources: FAO 2005, de Noblet-Ducoudré and Peterschmitt 2008)

That version used historical population maps (urban and rural) as a basis for the allocation of land cover and time-dependent weighting maps for cropland and grassland (Klein Goldewijk 2007). Reconstructed changes in both historical croplands and pastures have been linked to the history of human settlement, population density, paths of economic development and climate.

De Noblet – Ducoudré and Peterschmitt (2008) have provided the datasets of global geographic distribution of crops and pastures for the period 1850 – 2000 with a 5' spatial and 1 year temporal resolution. The datasets were compiled from the recent developments of the Ramankutty and Foley cropland dataset (Ramankutty *et al.* 2008) and Klein Goldewijk datasets of crops and pastures within the HYDE-3 database (Klein Goldewijk *et al.* 2007)

3.2.2 Data pre-processing

In order to produce a unique continuous dataset of crops and pastures for the period 1700–2000 I first combined the available historical datasets of crops (1700–1992 and 1850–2000), and pastures (1700–1990 and 1850–2000) in two separate datasets of crops and pastures for 1700–2000. These datasets helped me to estimate the contribution of the LULCC to climate from different perspectives; in particular, to estimate the difference between the crops–only driven LULCC simulations and the crops+pasture driven simulations (see Section 4). To merge the different datasets I used the IDL 7.1 program complex (© 2008 ITT Visual Information Solutions), which allows a step by step per year and per grid cell comparison, weighting and visualization of spatially referenced data. As a general algorithm for combining the overlapping datasets I integrated in the calculations an option to replace any diverging data in a grid cell with the most recent information. However, in this particular case no data were transformed in the merged series as the new datasets were derived based on their preceding versions and the overlapping parts were, therefore, identical.

A more complex methodology was used to compile a new extended historical dataset of agricultural landuse 1700–2000 including both crops and pastures. I started from the described above separate datasets of crops and pastures and derived an algorithm to fill a new grid with the combined data. For the combined maps, if only crops or only pastures were found in a given grid cell, then the area provided by the original dataset was kept unchanged. If both crops and pasture coexisted within the same grid cell, then the pasture area was restricted to the 'free' part of the grid cell, and the total extent of the grid cell was a summation of the two areas. If the sum exceeded the total area of the grid cell, then the extent of both crops and pastures has set to the full extent of the grid cell (see also Appendix B, Figure 3.2.2B: a and c).

3.2.3 Creating the model specific datasets

In order to drive the UVic ESCM based simulations the spatial grid of the new datasets had to be adjusted in its shape and size to fit the model spatial grid. This task was also completed with use of the IDL 7.1 program complex (© 2008 ITT Visual Information Solutions).

The model global space is defined as a series of volumes between six coordinates: two geographic latitudes, two longitudes and the surface of a spherical body in the rotated frame of reference. Thus, the horizontal spatial resolution of a model grid to which our maps have to be adjusted varies between the depths. However, similarly to many other two-dimensional processes in the model, the areal fractionation of a grid cell can be normalized and the value assigned as an attribute value to the centroid of the grid cell. The UVic ESCM grid divides the projected surface into 100*100 cells with a spherical grid resolution of 3.6° (zonal) by 1.8° (meridional). We used a weighted interpolation technique and the merging algorithm described in the previous section to create three continuous, normalized and spatially consistent datasets covering 300 years of agricultural activities: two for 1700 – 2000 crops and pastures distribution and a combined one for the same period including all the described agricultural land (see also Appendix B, Figure 3.2.3B: b, d and e).

3.2.4 Inclusion of new datasets into the model

These datasets were further integrated in the UVic ESCM and used to run our model experiments. However, as only one dataset at a time may be used to drive a simulation, it is important to note that in order to perform three separate model experiments with three different datasets, for each experiment the appropriate model input file has to be modified separately and the model has to be equilibrated anew.

3.3 Model description

This work is completed with the UVic ESCM version 2.8 (2008), modified in order to integrate the LULCC dynamics. The UVic ESCM is an intermediate complexity coupled climate–carbon model with dynamic sea-ice and dynamic vegetation. This implies that major carbon cycle/ climate feedbacks, including strengthened ocean and terrestrial carbon uptake (due to the elevated CO_2 and the effect of climate warming on ocean biological productivity, circulation and carbon solubility), as well as weakened carbon sinks (due to accelerated soil carbon decomposition and declined tropical vegetation productivity), are simulated dynamically by the model. In addition, the model is constructed on a modular basis so that an additional subset of processes or a submodel may be included depending on the particular concern or question of interest.

3.3.1 Earth-system Models of Intermediate Complexity (EMICs)

As was noted above, the UVic ESCM is a model of reduced complexity. This class of models includes explicit description of the majority of Earth-system components and processes though in a simplified form, often parameterized in relation to a specific simulation. The main gain of this approach is quite obvious – it provides an option to perform comprehensive simulations with reasonable resolution in a short time and with a reasonable computational cost. The models of this class are usually placed in the model hierarchy between the complex coupled GCMs and the oversimplified intuitive box models (Claussen *et al.,* 2002, see also Appendix C, Figure 3.3.1C: b).

3.3.2 UVic ESCM

Compared to other models of intermediate complexity the UVic ESCM incorporates a better ocean model, a quasi-dynamical ice-sheet model, as well as more sophisticated sea-ice and snow models. These qualities, coupled with its interactive modular structure, position the model at the more comprehensive end of the EMICs hierarchy (Claussen *et al.,* 2002, Weaver *et al.* 2001, see also Appendix C, Figure 3.3.1C: a).

The single big limitation pertinent to the UVic ESCM as a model is its simplified representation of the atmosphere. Though, often this is also an advantage as it allows for easier sensitivity analysis including atmospheric carbon and climate/carbon feedbacks, and also allows using a more developed than in many of EMICs ocean component while not overloading the overall computational efficiency of the model. Other limiting factors include cloud feedbacks and internal tropical variability that have simplified parameterizations and are not dynamically integrated in the model climatology. However, those limitations, although increasing the overall uncertainty of the model simulations, do not bear a significant additional error in our estimates as they are not linked directly to the integrated new scheme, and the model was calibrated over the preindustrial conditions before the relevant transient simulations were run.

The core components of the UVic ESCM are: a three-dimensional ocean General Circulation Model (GCM) coupled to a thermodynamic/dynamic sea ice model, an energy-moisture balance atmospheric model of reduced complexity with dynamic feedbacks, and thermo-mechanical land ice model (Weaver *et al.* 2001). Its current version also includes a dynamic global vegetation model.

The ocean component of the model is based on the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model 2.2 (MOM 2.2). This is a 19 – level GCM coupled to a dynamic-thermodynamic sea ice model. The sea ice component describes sea ice thermodynamics and thickness distribution and incorporates an elastic-viscous-plastic rheology to represent sea ice dynamics. It also includes a full ocean carbon cycle model (including ocean biota), an ocean chemistry model and an ocean biology model (Schmittner *et al.* 2008).

The atmospheric module includes parameterization of water vapour and planetary long wave feedbacks. Radiative forcing in the UVic ESCM is specified as a function of the simulated atmospheric CO_2 relative to the reference CO_2 concentration (Weaver *et al.* 2001). Ice and snow albedo feedbacks are included in the coupled version of the model through the planetary albedo alteration. Topography in the model is described through the specific lapse rates modifying the land surface air temperature. Atmospheric heat and freshwater transports are realized through diffusion and advection by specified winds. Precipitation is parameterized trough relative humidity and is assumed to occur if the relative humidity exceeds 85%. Surface wind stress and vertically integrated atmospheric winds are specified from the Reanalysis Data of the National Centres for Environmental Prediction, Maryland (NCEP) (Matthews *et al.* 2004, Matthews *et al.* 2005b, NCEP 2007).

Land surface dynamics, the terrestrial part of carbon cycle and vegetation dynamics are represented in this version of the UVic ESCM by an adapted version of the Hadley Centre's MOSES-2 scheme (Met Office Surface Exchange Scheme - MOSES) coupled to the DGVM TRIFFID (Meissner *et al.,* 2003; Matthews *et al.,* 2005b). This part of the model is part of the focus of this study, and its complete structure, functioning and feedbacks, both included and not included, are discussed in subsequent sections.

3.3.3 Land use in the model

The land surface scheme used within the UVic ESCM v. 2.8 includes the Hadley Centre (UK) carbon cycle and dynamic vegetation model TRIFFID ('Top-down Representation of Interactive Foliage and Flora Including Dynamics', Cox *et al.* 1999, Cox 2001) driven by the net carbon fluxes generated via a one-layer model based on the 'Met Office Surface Exchange Scheme' MOSES-2.2 (Essery *et al.* 2001). The scheme assumes a dynamic areal competition of five PFTs in response to simulated climatic conditions and area availability, and also calculates changes in the vegetation and soil carbon pools and associated carbon fluxes. A terrestrial bioenvelope for the five PFTs (broadleaf trees, needleleaf trees, shrubs, C3 and C4 grasses) is simulated by the DGVM TRIFFID and then the two models simulate energy, moisture and carbon exchange at the land - vegetation - atmosphere interfaces for each PFT at an hourly time step (Meissner *et al.* 2003, Matthews *et al.* 2005a).

For simulating the grid box specific ecosystem processes the TRIFFID/MOSES scheme incorporates a biochemical model of photosynthesis, current vegetation Leaf Area Index (LAI, approximated as a fraction of carbon balance of the whole plant), and calculates Net Primary Productivity (NPP) as a difference between the Gross Primary Productivity (GPP) and the autotrophic Respiration (R_a): NPP = GPP – R_a. The resulting carbon flux contributes to both vegetation growth and PFT expansion which are limited to non-agricultural areas.

The major advantage of this scheme for simulating the anthropogenic land cover change impacts is that natural vegetation which has been dynamically calculated by the UVic ESCM can be combined with explicit LULCC data. However, the scheme also has a limitation that may eventually introduce a significant bias into the estimates of the net ecosystem carbon exchange. This limitation arises from the simplified redistribution of vegetation carbon following land cover change. The vegetation carbon is transferred as a result of land use change to a single soil carbon pool (via litterfall) and then returned to the atmosphere by heterotrophic respiration (decomposition); thus the amount of carbon removed from the site after land clearing is not included in the calculations.

3.3.4 Model development

To better represent the effects of LULCC on carbon budget I have introduced a new carbon accounting scheme in the UVic ESCM v.2.8 terrestrial component (see Appendix C). The scheme is based on the bookkeeping approach (Houghton 1983, 1999, Houghton and Hackler 1995, 2001, Strassmann *et al.* 2008). The original (Houghton's) bookkeeping model (hereafter HBM) distributes the vegetation carbon available after land clearing between three carbon pools: live stands, left-on-site material and removed-from-site material (Houghton 1983). The HBM further tracks the rate at which the cleared vegetation pool replenishes to its original volume, while the left-on-site and removed-from-site materials decay at specified rates. Time steps and decay coefficients in the HBM are prescribed by region and by land-use/ecosystem type. The changes in the left-on-site and removed-from-site carbon pools provide estimates of the carbon flux to (decay) and from (replenishment) the atmosphere (Houghton and Hackler 1995).

Within the UVic ESCM v.2.8 I use a dynamic approach to calculate the global land use change related fluxes. The calculations are based on tracking the LULCC carbon transitions between six terrestrial carbon pools, each with different biophysics, biogeochemistry and time scales: live vegetation, soil carbon, harvested carbon, two wood product pools and the atmosphere (Fig. 3.3.1, see also Fig. 3.1.1 on p.23). The new scheme extends the original HBM by two added short- and long-lived wood product carbon pools and also couples the scheme to the UVic ESCM thus extending the original TRIFFID/MOSES carbon accounting scheme by a dynamic loop including those additional carbon pools. Within this new scheme, the carbon residing in the live stands and the soil carbon pools is calculated dynamically as part of the DGVM TRIFFID. Furthermore, within the MOSES scheme (see Section 3.3.2 for reference) I interactively calculate the allocation of carbon to short- and long-lived wood product pools following specified land cover change and use varying decay timescales to estimate the associated CO_2 fluxes to the atmosphere. The initial change in the vegetation carbon associated with land use change (harvested carbon pool) is referred to in the UVic ESCM v.2.8 as a 'burnt' fraction of agriculture (hereafter referred to as *HARV_BURN* variable). This fraction in the model has an interactive modifying parameter (hereafter - *BF* variable) which regulates the amount of carbon available for further redistribution - i.e. the magnitude of the fraction of carbon after land clearing which is not transited directly to the soil carbon stock on the site (as a litterfall or the harvest residuals) but was removed from the site in some form (hereafter H_t variable, where $H_t = BF * HARV\_BURN_t$).

This removed at time t amount of carbon H_t further decays according to an exponential function:

$$H_{t+1}^{out} = H_t e^{nt} \tag{3.3.4.1}$$

where: H_t - carbon in pools at time t, and H_{t+1}^{out} is the decayed fraction of that carbon

t - model time step

n - decay constant, (interactive, specific to pool, where $n<0$, and $[n] = [1/t]$)

The decayed fraction H_{t+1}^{out} further determines the change in carbon emissions attributed to land use change, which will be added at the next time step to the calculated at that next time step total land use carbon emissions (hereafter referred to as E_{LU} (or '*BURN*') variable), thus forming the total land use carbon emissions at that time step.

Therefore at each time step t the total land use emissions become:

$$E_{LUt} = BF * HARV\_BURN_t - SH_t^{in} - LN_t^{in} + \Delta E_{LU(t-1)} \ , \tag{3.3.4.2}$$

where: $$\Delta E_{LU(t-1)} = SH_{t-1}{}^{out} + LN_{t-1}{}^{out} \ , \tag{3.3.4.3}$$

and: HL- *direct C emissions* ($HL<1yr$), including $HL_t = k_{HL} * H_t = 0.3H_t$,

SH- *fast decay pool* ($1<SH<2$ *yrs*), including $SH_{in} = k_{SH} * H_t = 0.2H_t$,

LN- *long decay pool* ($2<LN<20yrs$), including $LN_{in} = k_{LN} * H_t = 0.5H_t$,

and also including: $$SH_{out}(t) = SHe^{n_{SH}t} = SHe^{(-0.0354)t} \tag{3.3.4.4}$$

and $$LN_{out}(t) = LNe^{n_{LN}t} = LNe^{(-0.00353)t} \ . \tag{3.3.4.5}$$

where n is the decay constant (see Notes to the equation (3.3.4.1) and Table 3.3.1 for reference).

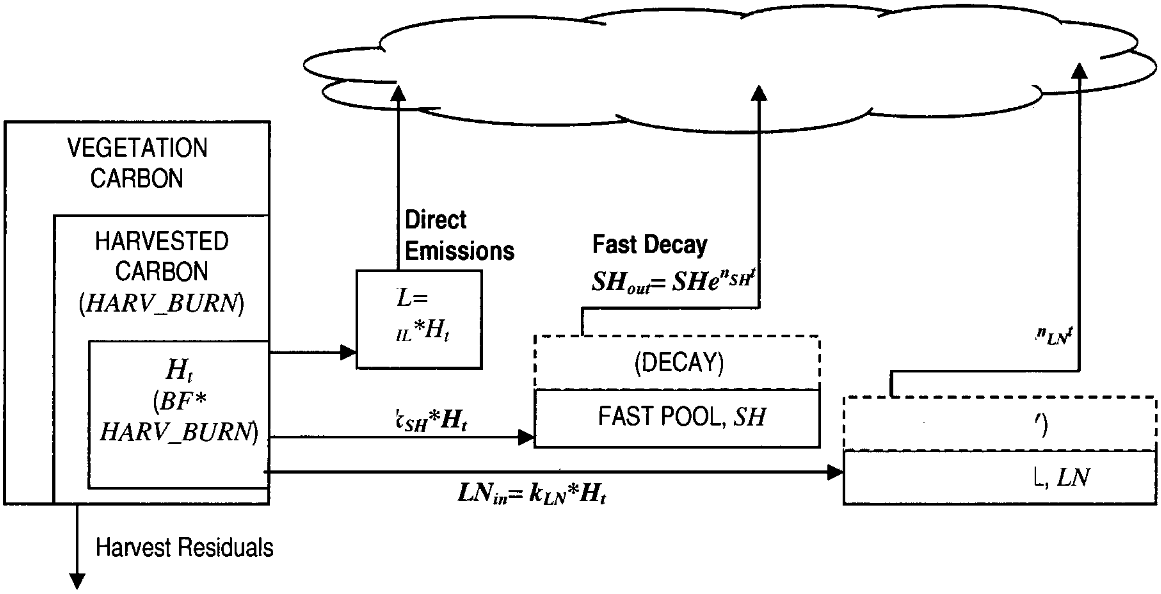


Figure 3.3.1. Comprehensive scheme of the LULCC carbon allocation in the modified version of the UVic ESCM v.2.8

Hence, the available for the redistribution by the model (i.e. decayed) at each time step t fraction of the harvested carbon dH_t becomes:

$$\frac{dH_t}{dt} = E_{LU}(t) = k_{HL}H_t + \frac{dSH_t}{dt}e^{n_{SH}t} + \frac{dLN_t}{dt}e^{n_{LN}t}, \qquad (3.3.4.6)$$

where $$\frac{dSH_t}{dt} = SH_{in}(t) - SH_{out}(t) \quad ,$$

and $$\frac{dLN_t}{dt} = LN_{in}(t) - LN_{out}(t) \quad ,$$

or otherwise (using 3.3.4.4) $$\frac{dSH_t}{dt} = k_{SH}H_t - SHe^{n_{SH}t} \quad ,$$

and (using 3.3.4.5) $$\frac{dLN_t}{dt} = k_{LN}H_t - LNe^{n_{LN}t} \quad .$$

Then, using (3.3.4.6), and providing that (from 3.3.4.3)

$$LN_t = k_{LN}*H_t + LN_{t-1} \qquad (3.3.4.7)$$

and

$$SH_t = k_{SH}*H_t + SH_{t-1}, \qquad (3.3.4.8)$$

the $E_{LU}(t)$ becomes:

$$E_{LU}(t) = k_{HL}H_t + (k_{SH}H_t + SH_{t-1})e^{n_{SH}t} + (k_{LN}H_t + LN_{t-1})e^{n_{LN}t} \qquad (3.3.4.9)$$

The appropriate fractions k of the initial carbon H_t in the decaying wood product pools were specified according to Andrasko (1990) and the Food and Agriculture Organisation of the United Nations (FAO 2008) estimates, while the pool specific decay constants n_n were assigned based on the estimates provided by Skog *et al.* (2004) and Strassman *et al.* (2008), which assumed the average decay rates of the short- and long-lived wood products of 2 and 20 years respectively. Accordingly, in the current model experiment the total decaying ('burnt') fraction of carbon H_t was redistributed as follows:

Table 3.3.1. Parameterization of the wood product carbon pools

Fractionation	**Fraction Volume** (% of initial value)	**Rate of decay**	
		2 half-lives	decay constant
Lost Harvest (*LH*) (*Direct emissions*)	30%, ($k_{HL}=0.3$)	0yrs	$n = -1$
Short-lived (*0 to 2 yrs*) carbon pool (*SH*)	20%, ($k_{SH}=0.2$)	2yrs	$n \approx -0.0354$
Long-lived (*2 to 20 yrs*)	50%, ($k_{LN}=0.5$)	20yrs	$n \approx -0.00353$

carbon pool (*LN*)			
Notes: The appropriate decay constants derived from the half-lives of the long- and short-lived fractions of the initial carbon H_t respectively. Providing that at $t_{1/2}$=10yrs (and 1yr) the size of the pool $H_{t(1/2)}$=0.65 H_t, the decay constant n was be calculated from $0.65H_t = H_t e^{-10k} \Rightarrow k=ln(0.65)/10yrs\ (1yr)$, where the years were calculated in model time steps.			

The *BF* fraction in this model experiment was specified as $BF=0.7$, in accordance with Skog *et al.* (2004) and the FAO (2008) data suggesting that on the global average about 70 - 72% of the 'harvested' wood is removed from a site after a clear-cut. The Results section of this work also presents the analysis of the model sensitivity to the *BF* variable.

3.3.5 Carbon balance verification

The new integrated scheme of carbon allocation, besides the fractionation of the LULCC related carbon emissions, creates two additional intermediate carbon pools in the model and specifies their decay timescale thus creating carbon emissions to the atmosphere. However, these additional pools do not produce additional carbon independently from the natural global carbon cycle. Thus, the total amount of carbon available to the UVic ESCM, whether it is in the soil, atmosphere, trees or any other intermediate pools, has to remain constant in the model in order to satisfy the mass conservation law.

The consistency of the carbon balance through the model simulations can be verified, which will also support the accuracy of the modifications made to the model math and the model code. The total amount of carbon involved in the carbon cycle in the UVic model (C_{total}) consists of the total carbon stored in the land (LC), the ocean (OC) and the atmosphere (AC):

$$C_{total} = LC + OC + AC \tag{3.3.5.1}$$

Since the model does not include processes neither creating nor destroying carbon, this balance can only be changed due to exogenously added carbon, specifically through the specified anthropogenic CO_2 emissions entering the atmosphere and thus the carbon cycle. Hence, this change in the total model carbon ΔC_{total} may be calculated as

$$\Delta C_{total} = \Delta LC + \Delta OC + \Delta AC = E_{FF} \tag{3.3.5.2}$$

where: E_{FF} - specified Fossil Fuel emissions

and the change in the atmospheric carbon AC then becomes

$$\Delta AC = E_{FF} - \Delta LC - \Delta OC \tag{3.3.5.3}$$

or

$$\Delta AC = E_{FF} - (\Delta CS + \Delta CV) - (\Delta DIC + \Delta C_{bio}) \tag{3.3.5.4}$$

since the land carbon LC is a sum of the soil carbon CS and the vegetation carbon CV while the ocean carbon OC consists of the dissolved inorganic carbon DIC and the carbon trapped in marine biota C_{bio}.

LULCC redistributes the vegetation carbon ΔCV in the system between the soil (CS) and the atmospheric (AC) carbon. However, in the modified version of the model, used in this model experiment, the carbon stored in wood products is temporarily removed from the equilibrium described by (3.3.5.1). Therefore, in order to verify the model carbon consistency in this experiment, the wood product carbon C_{wp} from two additional pools has to be added into (3.3.5.4) in order to account for all the carbon in the system. Hence, if written in terms of the CO_2 emissions and rearranged the equation (3.3.5.4) becomes:

$$E_{FF} - (\Delta CS + \Delta CV) - (\Delta DIC + \Delta C_{bio}) - \Delta C_{wp} - \Delta AC \approx 0 \qquad (3.3.5.5)$$

where the added term ΔC_{wp} stands for the carbon stored in the intermediate carbon pools. If the equality holds through the simulations then the model contains no carbon either miraculously added or removed, and, thus, the performed modifications are mathematically correct and the simulations are valid.

Figure 3.3.1 shows an example of such a verification. In this example the equation (3.3.5.5) was solved for the the UVic ESCM v.2.8 in the simulation driven by the combined dataset of crops and pastures from 1700 to 2000. The calculations and plotting performed using a specifically developed for that purpose program (an IDL 7.1® based script). The presented plot is the graphical output of the IDL 7.1® complex showing ΔC_{total} (GtC) over 1700 to 2100 model years at X (horizontal) axis. The graph shows a zero ΔC_{total} yearly balance for the 'Diagnosed CO_2 Emissions' in the model (i.e. calculated based on the carbon inputs, green dashed line), and a virtually zero ΔC_{total} balance solved for the total of simulated stocks (red line) that fluctuates in accordance with the model carbon transitions.

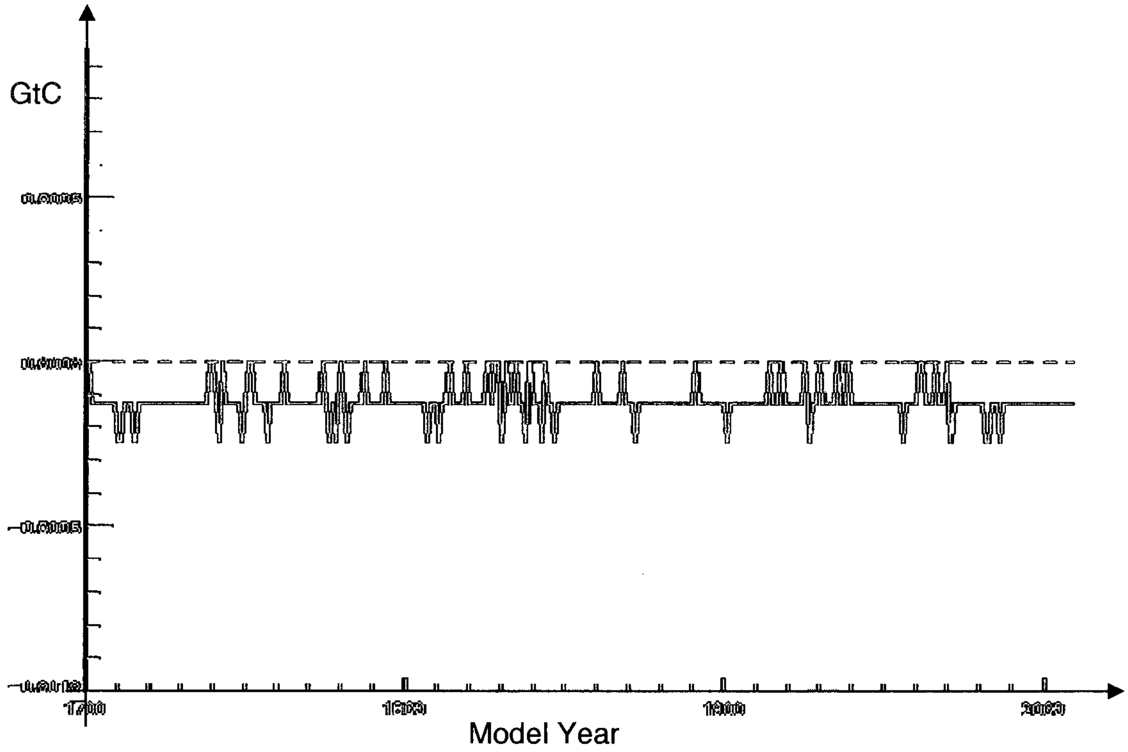


Figure 3.3.2. **Carbon balance verification (GtC/yr): ΔC_{total} diagnosed (green dashed line) and ΔC_{total} modeled (red line; Note: the negative ΔC_{total} modeled balance does not include carbon in the intermediate reservoirs between the model time steps)**

3.4 Model simulations

I have run a series of transient simulations using this modified version of the UVic ESCM v.2.8 in order to estimate the unbiased values of the LULCC emissions. I used the three datasets of crops and pastures from 1700–2000 (see Chapter 2) to drive the model. In order to ensure the model was in an equilibrium condition consistent with preindustrial conditions and was suitable for the targeted perturbation sensitivity analysis several steps had to be performed before the transient runs. The essentials of those initial steps are described in the next sections.

3.4.1 Model equilibration and validation

The UVic ESCM consists of several models with timescales ranging from seconds to millennia and was coupled in a system capable of recreating processes forming the Earth system dynamics. In order to equilibrate these components under the appropriate radiative forcings (in this case – to the year 1700, preindustrial conditions) the coupled model has to be 'spun-up' for a period sufficient to reach an equilibrium climate free of internal variability, heteroscedasticity and inertia. For the UVic ESCM v.2.8 this period may vary between several hundreds and several thousands of years depending on the model restart conditions. This is to say that if the variables with the longest adjustment time (e.g. deep ocean regions) have been modified, the spin-up period of thousands of model years will be appropriate. Otherwise, a valid model spin-up can be based on the pre-equilibrated ocean component and pre-initialized terrestrial components, and, thus, can normally be completed in several hundred model years (a few days of computer time). This method is widely used by the scientific community and helps to save a significant amount of computer time and overall computational costs. As long as the modifications made to the UVic ESCM v.2.8 in this work were integrated in its terrestrial part with generally shorter time scales, the latter, 'short' method of equilibration had been used. The model was spun-up for 700 relative model years starting from the pre-equilibrated boundary conditions (10 000 model years continuous equilibrium run, available in the Climate Change

Lab, Concordia University). Figure 3.4.1 shows that the modified version of the UVic ESCM v.2.8 reached the climate consistent with the preindustrial condition by the end of the several hundred years run.

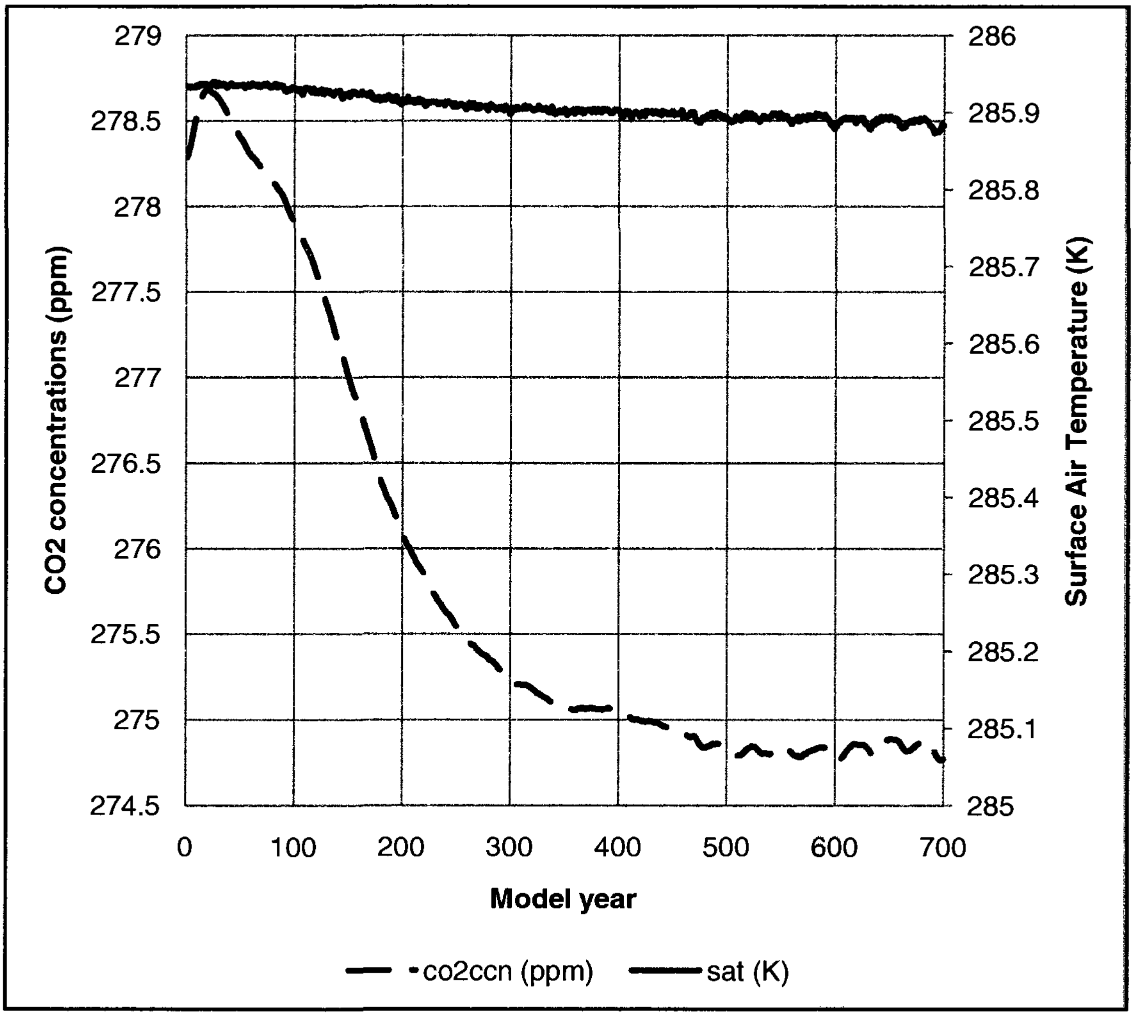


Figure 3.4.1. The UVic ESCM v.2.8 equilibrium run including the intermediate (wood product) carbon pools: global average CO_2 concentrations (ppm) and Surface Air Temperature (SAT, K)

The model was brought to equilibrium starting from the specified year 1700 landcover data and with 'free CO_2' (i.e. the atmospheric CO_2 concentrations were dynamically simulated by the model). The resulting state was stable with negligible fluctuations in the global average modeled atmospheric CO_2 concentrations over the long-term run.

Figure 3.4.1 presents the spin-up completed with the model-dataset configuration used to run the main series of transient simulations in this experiment. Similar equilibrium runs were completed for each model-dataset combination (see Table 3.4.1). The table shows the range of residual discrepancies between the equilibrium climate in the model and the observations for the same period in order to demonstrate that for every combination of parameters the model had reached the satisfactory equilibrium climate and, thus, provided valid boundary conditions used later to run the transient climate simulations.

Table 3.4.1. The UVic ESCM equilibrium run global average CO_2 concentrations (ppm) and Surface Air Temperature (SAT, K) comparison against the observed values of the CO_2 concentrations (Etheridge et al. 1998) and Surface Air Temperature (Petit et al. 2000)

Model scheme	Model CO_2 concentrations, ppm	Δ from Data, ppm	Model Surface Air Temperature, K	Δ from Data, K
NBK + CP	278.4	+1.7	286.11	-0.06
BK +CP (C3+C4)	274.8	-1.9	285.87	-0.30
BK + C	274.8	-1.9	285.88	-0.29
BK + CP (C3)	275.9	-0.8	286.02	-0.15
BK + CP (C4)	278.3	+1.6	285.93	-0.24

BK + CP (BL)	277.3	+0.6	285.89	-0.28
Data, 1700AD	276.7		286.17	

For each equilibrium run, the model was forced by the constant extent of agricultural land while the atmospheric CO_2 concentrations were simulated by the model in order to attain a dynamic equilibrium. Five model-dataset configurations were used in this study. First (NBK + CP) was the original version of the UVic ESCM v.2.8 (with no modifications included) with a combined dataset of crops and pastures used to drive the run. The second model run included the bookkeeping scheme and was driven by the same land use data (BK+CP). It should also be noted that the agricultural land in this scheme was represented by the naturally competing C3 and C4 grass PFTs. The third run used a similar configuration but replaced the combined crop and pasture area with the crops only dataset (BK + C). This experiment, along with the first one, served as a baseline for the transient simulations as the crop-only dataset has been the most commonly used for the LULCC estimates, and this possibly leads to a significant underestimation of the LULCC related emissions. Two last spin-ups (BK+CP, C3 and BK+CP, BL) were intended to provide a valid boundary condition for the experiment in which I replaced the natural grasses competition on the land restricted to agriculture, with the prescribed PFTs: the transient runs with C3 grasses only, C4 grasses only and Bare Land only were completed.

3.4.2 Model setup

The equilibrium simulation represents a stable climate that matches prescribed (constant) forcing, and is thus suitable as the starting point for a perturbed or transiently forced simulation.

Table 3.4.2. Model setup combinations used in transient simulations.

Model scheme	Land Use Dataset	Period
NBK + CP	RF99, HYDE-2	1700 - 1990
	RF99, HYDE-2, NDP3	1700 - 2000
BK +CP	RF99, HYDE-2	1700 - 1990
	RF99, HYDE-2, NDP3	1700 - 2000
BK + C	RF99	1700 - 1990
	RF99, NDP3	1700 - 2000

RF99: Ramankutty and Foley (1999), Global historical distributions of croplands from 1700 to 1992, 0.5 degree spatial and 1 year temporal resolution.

HYDE-2: Klein Goldewijk (2001), HYDE-2, reconstruction of the historical pastures from 1700 till 1900 with a 0.5 degree spatial resolution and 50 years temporal resolution.

NDP3: De Noblet – Ducoudré and Peterschmitt (2008), Global geographic distribution of crops and pastures for the period 1850 – 2000 with a 5' spatial and 1 year temporal resolution, compiled from Ramunkutty and Foley cropland dataset (Ramankutty *et al.* 2008) and Klein Goldewijk datasets of crops and pastures within the HYDE-3 database (Klein Goldewijk *et al.* 2007)

In the current research the modified version of the UVic ESCM v.2.8 was forced by the prescribed (from data) CO_2 emissions from fossil fuel combustion and by the transient LULCC related emissions calculated by the model from the specified data on historical crops and pasture distribution. Table 3.4.2 presents all the combinations of land use datasets and periods used to run transient simulations in this study.

CHAPTER 4. RESULTS

This Chapter presents the results of a series of the fully coupled transient simulations designed to identify the land use flux uncertainty in the UVic ESCM captured by the new bookkeeping-based carbon accounting scheme grounded in the terrestrial part of the model. This study also provides an insight to the estimates of the net effect of the LULCC on the observed atmospheric CO_2 concentrations and, thus, to the estimates of the total human contribution to the current climate forcing.

4.1 Carbon contribution from croplands

The results of this model experiment conform to the estimates of the International Panel on Climate Change (PCC WG1 AR4). At present the carbon flux to the atmosphere attributed to LULCC is considered to be about 1.6GtC/yr (IPCC WG1 AR4 Table 7.1). The modified version of the UVic ESCM v.2.8 developed in this study simulates the year-2000 land use change flux of 1.94GtC/yr on the global average (see Figure 4.1.1, model setup BK+CP, datasets RF99, HYDE-2, NDP3 1700 – 2000, see Table 3.4.2 for reference). This estimate falls within the range of uncertainty provided in the last IPCC report, though surpasses the AR4 mean value by 0.34GtC/yr. This surplus can be in part due to the new and extended dataset of agricultural area used to drive the simulation: the extent of pastures was included in this work and was not in the IPCC assessment (Denman *et al.* 2007). Figure 4.1.1 demonstrates the historical growth of the carbon flux from agriculture for the years 1750-2000 (blue line) and also the historical extent of the agricultural area for the same period (green line).

These two values plotted in one figure in order to demonstrate a correlation between the two, which confirms the direct link between the two variables (the fossil fuel emissions were excluded from this simulation, thus the only present forcing here is the LULCC).

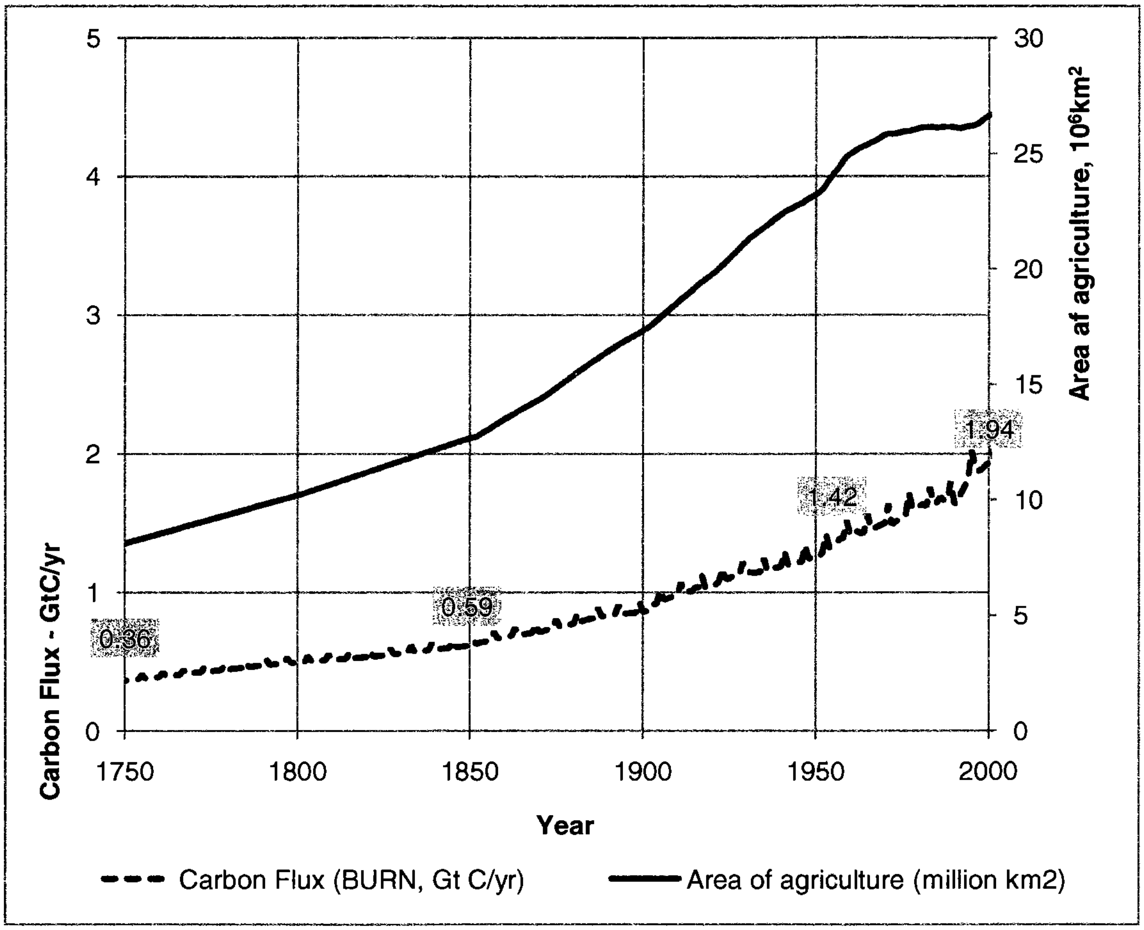
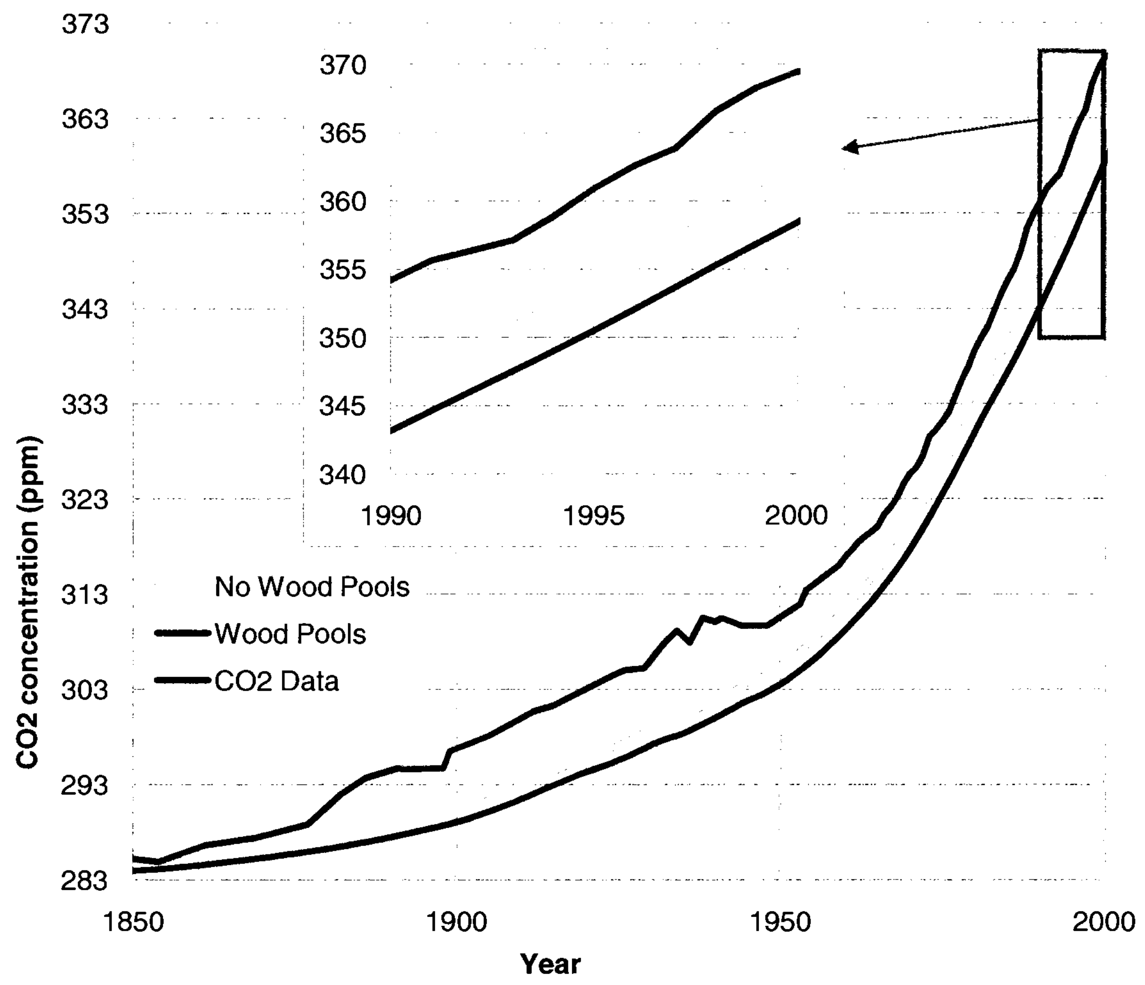


Figure 4.1.1. **Simulated global averaged carbon flux from land use change (Gt C/yr) and global combined area of agricultural land (million km^2) 1750 – 2000, model setup: BK+CP (see also Table 3.4.2 and Table 4.1.1E in the Appendix E)**

While the aforementioned fact is well known, it worth noting that a part of the observed steady carbon flux growth is ultimately due to the emissions from the wood product carbon pools that were not usually considered in the global climate model simulations. Although the carbon redistribution between those wood product pools were approximate in this work, the combination of their inclusion and the correction of the extent of agricultural land may have indeed improved the representation of the carbon flux from LULCC in the UVic ESCM, as this version of the model better reproduced the observed values of the current atmospheric CO_2 concentrations than the one without these areas and pools (see Fig. 4.2.1 in the next section). However, it can be also seen from Figure 4.2.1, that, compared to the observed CO_2, this version of the UVic ESCM, forced by the combination of the specified fossil fuel emissions and the transient LULCC related emissions, underestimated the year-2000 CO_2 concentrations by about 11ppm. This issue will be discussed in later sections.

4.2 Carbon accounting scheme in the model

Figure 4.2.1 shows the CO_2 concentrations (ppm) simulated for the period 1850-2000 both including the intermediate (wood product) carbon pools accounting for the amount of carbon both 'burnt' immediately and stored out of the natural carbon pools and omitting the such (i.e. the land use carbon emissions E_{LU} are distributed between the land and the atmospheric reservoirs immediately after allotment). Compared to the observed CO_2 concentrations it shows that if carbon stored in wood products is not calculated in the model the increase in the atmospheric CO_2 concentrations is overestimated by about 30ppm by the year 2000. That is to say that the overall simulated increase in the atmospheric CO_2 concentrations by the year 2000 was 79.7ppm if the carbon pools were included, which is 46.7ppm less compared to the simulation omitting those pools (126.5ppm).



Total change in CO_2 concentrations from 1859 to 2000 (ppm)	**Wood Product Pools included**	**No wood pools included**	**CO_2 observations**
	74.85	78.00	92.27

Figure 4.2.1. Simulated CO_2 concentrations (ppm) including and not including the intermediate (wood product) carbon pools, CO_2 Data (Etheridge *et al.* 1998, Marland *et al.* 2005)

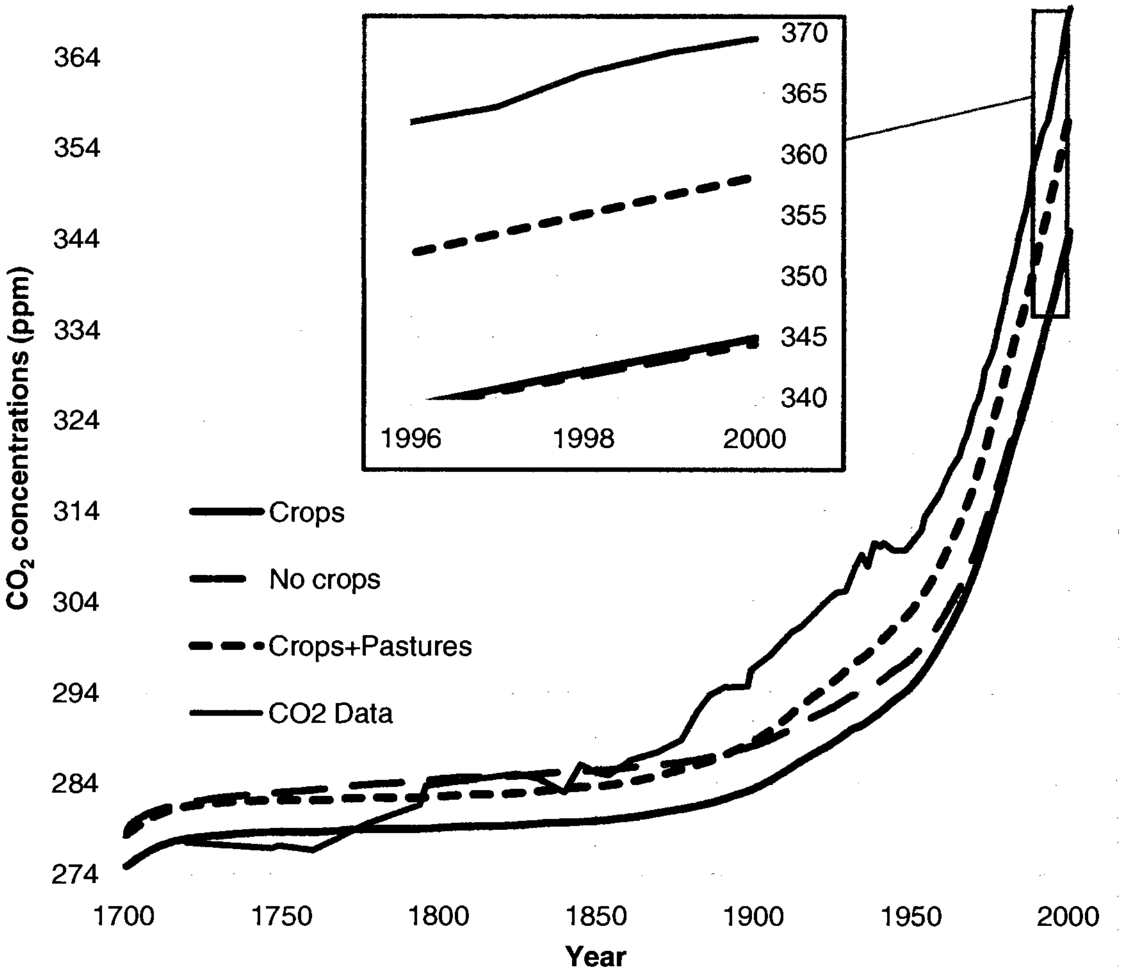
Therefore, the integration of the additional ‘wood product’ carbon pools is necessary to perform a better analysis of the model sensitivity to the LULCC emissions. For the purposes of further research this integrated carbon accounting scheme was made interactive, allowing user specific parameterization of the key variables and also leaving a possibility of including potentially available new and more comprehensive data in the calculations.

4.2 Sensitivity analysis

A series of transient simulations were performed in order to understand the sensitivity of the UVic ESCM to different biogeochemical and biogeophysical aspects of the land use changes and to estimate the net impact of the LULCC on carbon fluxes and climate change. For the evaluation of the results, the simulations including land use and driven by the extended dataset of crops and pastures, have been compared to the corresponding baseline simulations.

4.2.1 Sensitivity to different datasets

The transient model runs completed within this experiment have been driven by four separate datasets of crops and pastures combined in one continuous weighted series of global agricultural land use data and one continuous series of crop only data. The latter was compiled as a baseline dataset for the sensitivity experiments as many previous studies considered only the extent of cropland in the simulations and did not include the extent of pasture land (Brovkin *et al.* 2004). Figure 4.2.2 presents the atmospheric CO_2 concentrations as simulated by the modified version of the UVic ESCM v.2.8 in the run forced by prescribed fossil fuel CO_2 emissions (Etheridge *et al.* 1998, Marland *et al.* 2005) and model-calculated LULCC emissions from different spatial datasets of the LULCC distributions from 1700 to 2000.



Total change in CO_2 concentrations from 1700 to 2000 (ppm)	**Land use included ('Crops')**	**No land use included ('No crops')**	**Land use included ('Crops+ Pastures')**	**CO_2 observations**
	69.955353	65.516724	79.704101	92.270001

Figure 4.2.2. Simulated CO_2 concentrations (ppm) driven by the Fossil Fuel Emissions only, Crops only and Crops + Pastures datasets, as well as Data (Etheridge *et al.* 1998, Marland *et al.* 2005)

As can be seen from the Figure 4.2.2, if the crops only (RF99 + NDP3, see Table 3.4.2 for reference) dataset is used to drive the simulation, the LULCC related emissions are significantly underestimated by the model. However, if the complete dataset of agricultural land is used (RF99, HYDE-2, NDP3), a notably better reproduction of the instrumental CO_2 records is observed.

Although an overestimate of the data on CO_2 concentration can be seen (see Fig. 4.2.1) at the earlier stages (from 1700 to 1790) of this simulation driven by this extended land use dataset, the observed artefact may be of lower importance for the analysis here because of the scarcity of reliable data on both CO_2 concentrations and the extent of agricultural land for the period of question. Conversely, the overall positive difference between the outputs of two datasets is significant and will be discussed in the Section 5.

4.2.2 Sensitivity to different BF values

In order to ease future development of the UVic ESCM many components of the model have been made accessible and interactive. The vegetation carbon related to carbon emissions associated with land use change is referred to in the model as a 'burnt' fraction of agriculture (*BF*HARV_BURN*, see also Section 3.3.4 for reference). This fraction stands for the fraction of carbon which doesn't go directly to the soil carbon stock as a litter or harvest residuals after land clearing.

Figure 4.2.3 shows the estimated historical contribution of land use change to the direct global carbon emissions from 1700 to 2000 including both harvest determining immediate emissions and the decay of wood product pools, and Figure 4.2.4 – the corresponding global mean temperature change for that period. The choice of *BF* values is based on the assumption that the amount of woody biomass available for further redistribution after land clearing does not exceed 74% of its initial volume (Schimel *et al.* 2001, Skog *et al.* 2004, FAO 2008).

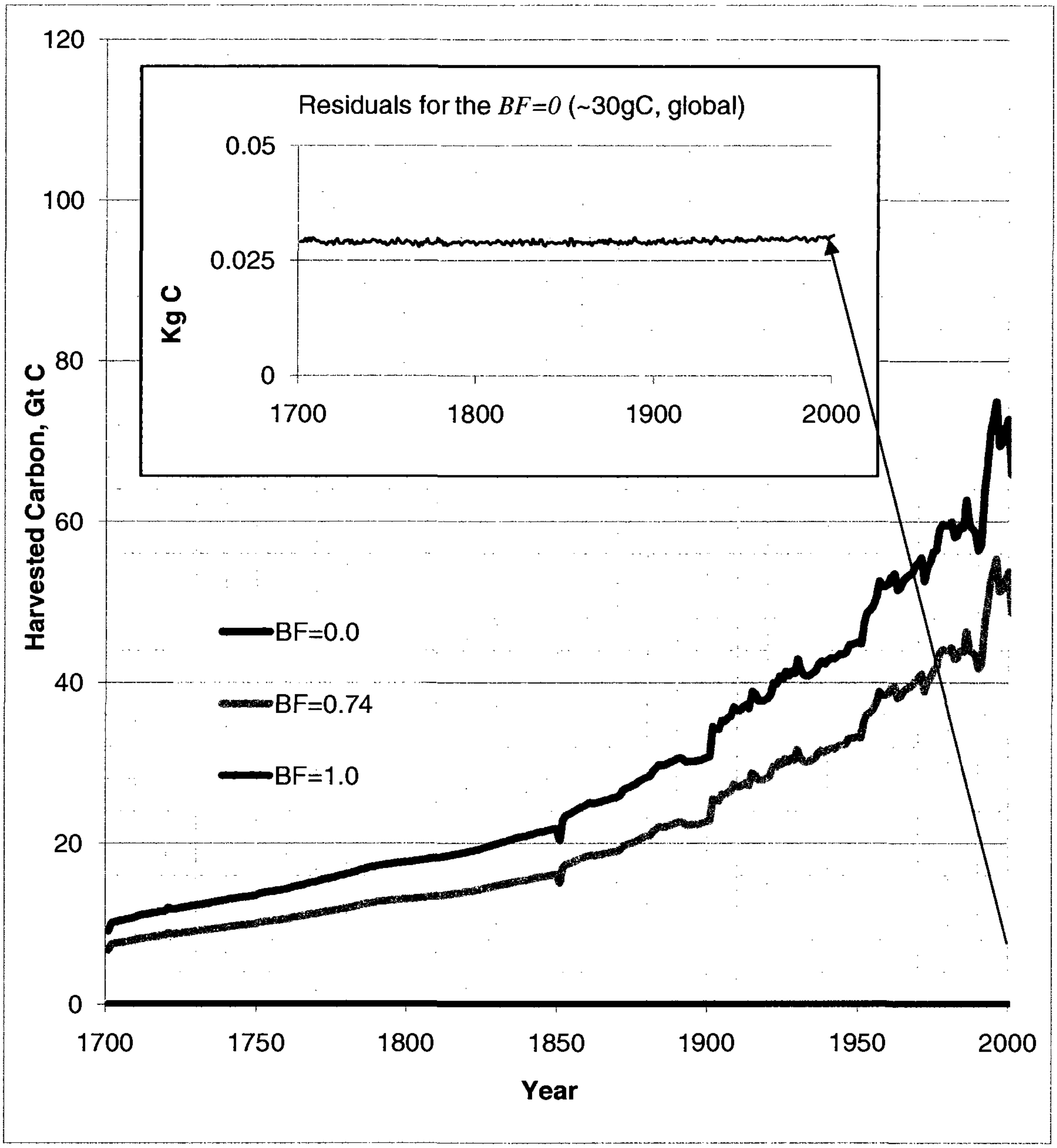


Figure 4.2.3. **Simulated global average LULCC related (harvested) carbon (Gt C) with extreme and actual values of the 'burnt fraction' of LULCC (BF, %), see also Table 4.2.3E in the Appendix**

The figures also show the extreme cases which assume 0 or 100% of the cleared woody biomass is redistributed to the intermediate pools respectively. Correspondingly, the historical contribution of the LULCC to direct carbon emissions is simulated to be about 50Gt C by the year 2000 with the extreme cases ranging from near 0 to about 70GtC (Figure 4.2.3).

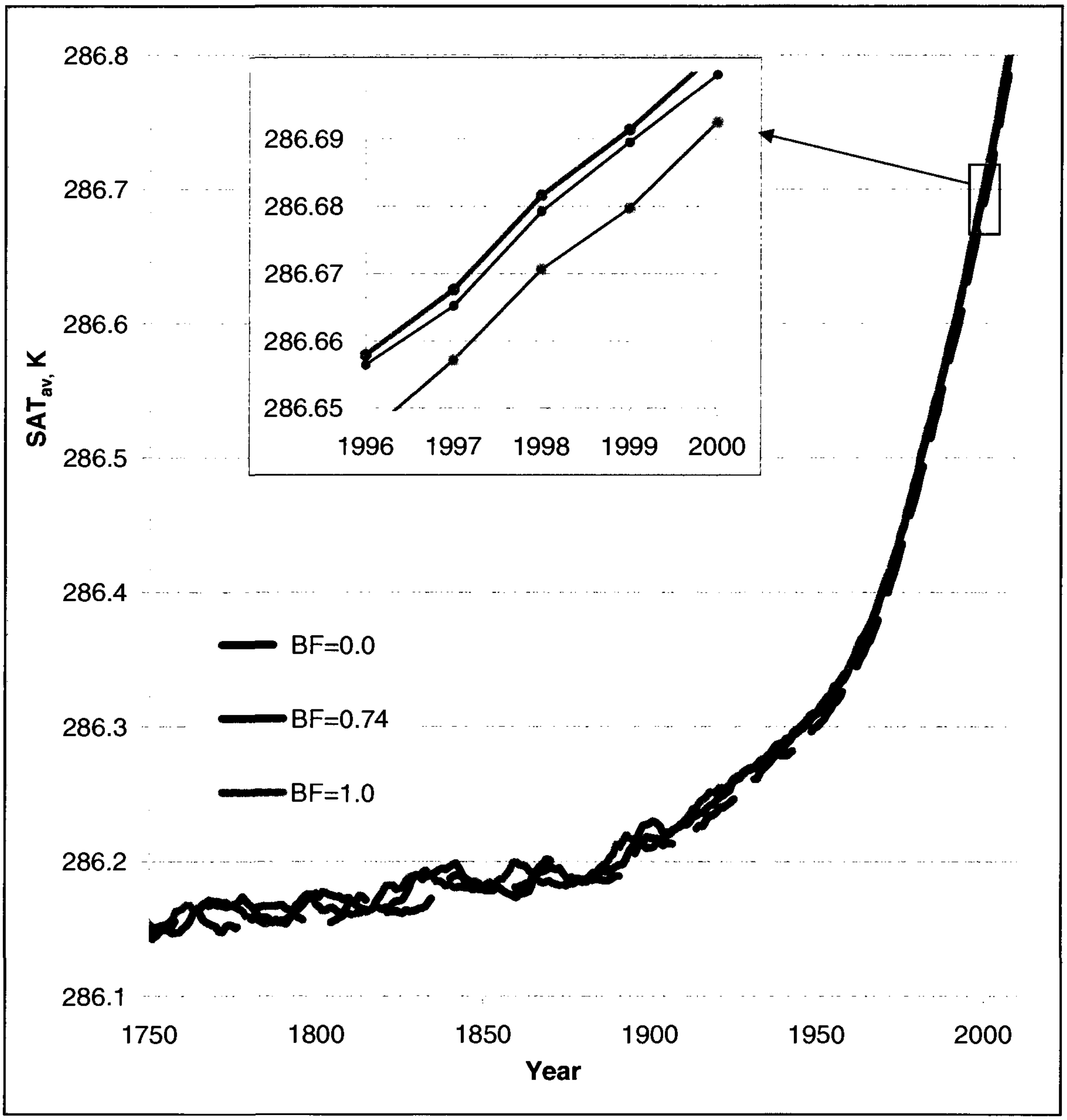


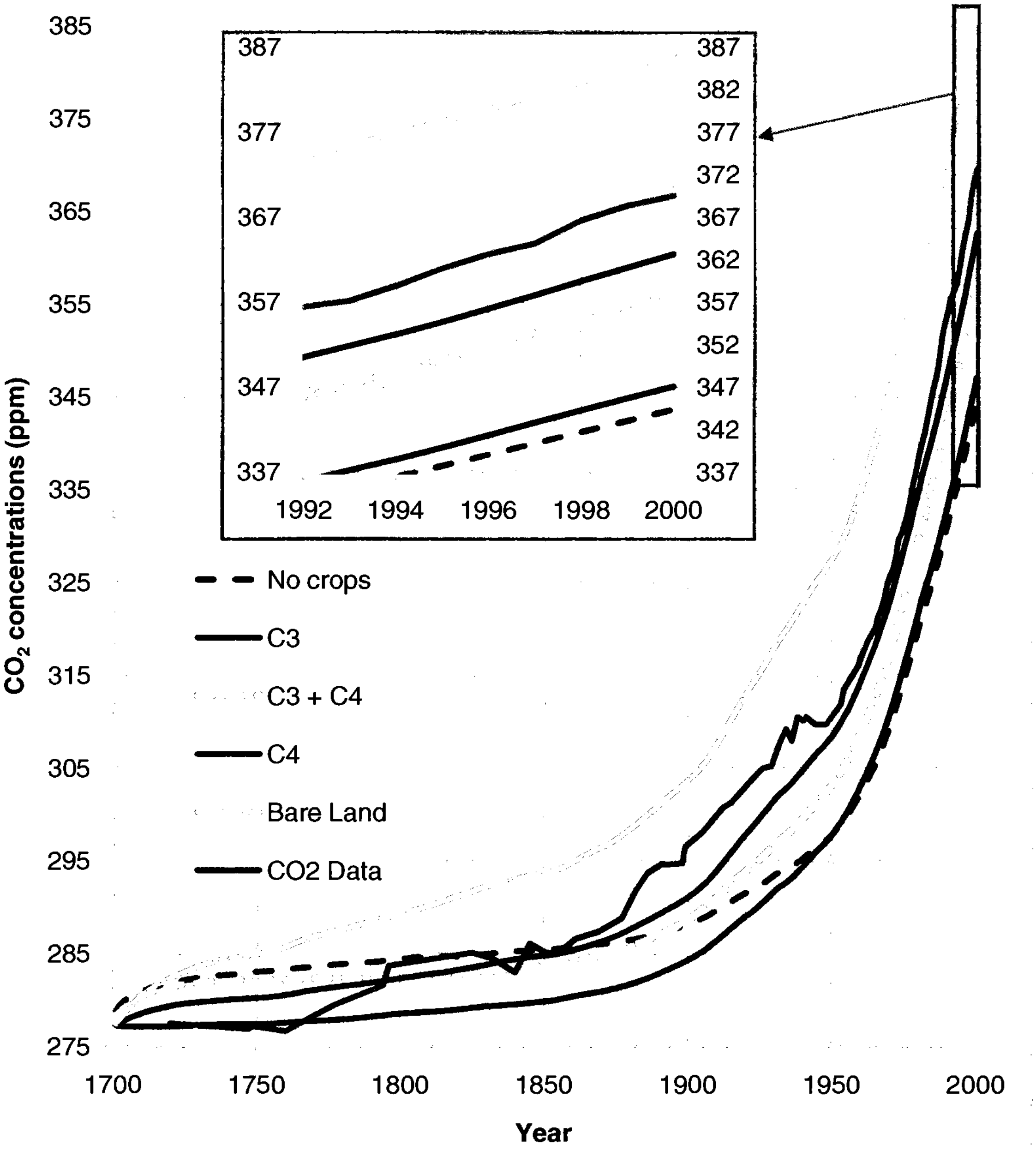
Figure 4.2.4. Simulated global average surface air temperature SAT(K) with different values of 'burnt' fraction of LULCC *BF*(%), (see also Table 4.2.4E in the Appendix E)

The respective contributions to the global temperature increase (Figure 4.2.4) ranges from 0 to 0.015K with approximately 0.01K corresponding to the BF value based on Skog *et al.* (2004) and the FAO (2008) estimates and used to drive transient simulations in this work.

4.2.3 Sensitivity to C3 – C4 grasses

In order to estimate the net total contribution attributed to the human induced land use changes I performed a series of experiments designed to grasp the uncertainty associated with the model representation of the agricultural land as naturally grown grasses. For this, the model code had been modified in such a way that for each simulation the area extent of agriculture was available to growth by C4 grasses only, C3 grasses only, or a mixture of the two (which is the standard model setup). An additional simulation was run with a condition that removed all growing vegetation from agricultural areas, leaving only bare ground. This 'Bare land' simulation represents an extreme case, which partly reflects the seasonal variations inherent to agricultural land, whereby tilled land is typically left bare for more than half of the year in many regions.

Figure 4.2.5 shows the CO_2 concentrations as simulated by the UVic ESCM with agricultural land represented in the model as C3 grasses, C4 grasses, a mixture of C3 and C4 grasses or as a bare land. This figure also contains reference information including the results of the simulation showing the Fossil Fuel Emissions only ('No crops' series, simulation without LULCC included) and the observed values of the atmospheric CO_2 concentrations.



Total change in CO_2 concentrations from 1700 to 2000 (ppm)	**Crops** C3+C4	**C3**	**No crops**	**Crops+ Pastures** C3+C4	**C4**	**Bare Land**	**CO_2 Data**
	69.956	69.759	65.517	79.704	85.252	108.732	92.27

Figure 4.2.5. Simulated global averaged CO_2 concentrations (ppm) for crops modeled as Bare land, C3/C4 grasses, C3+C4 grasses; for CO_2 data and No crops (simulation with no land use), see also Table 4.2.5E in the Appendix E

The simulated results show a 40ppm range in atmospheric CO_2 at the year 2000, depending on how crops are represented in the model. This highlights an outstanding area of uncertainty, and the need further research involving better simulation of crops phenology, biogeochemistry, and the effects of crop-pasture transitions and crop rotations, which is discussed in the Section 5.

4.3 Calculated land use carbon estimates

These results suggest that if the full agricultural extent is considered (i.e. crops and pastures), the historical contribution of the LULCC related CO_2 emissions, as simulated by the current modified version of the UVic ESCM v.2.8, seem to be responsible for about 14ppm of the atmospheric CO_2 concentrations above the typical previous estimates with the UVic ESCM v.2.8. In addition, the sensitivity analysis revealed the range of uncertainties associated with different biogeophysical and biogeochemical effects of possible different crops (e.g. C3 and C4), crops phenology (Crops as Bare land e.g. during the non-growing season), different types of land transitions and crop rotations. These effects may contribute to up to 30 ppm of additional CO_2 concentrations in the atmosphere (Figure 4.2.3). However, the current version of the model considers only a few of the biogeochemical effects associated with the agricultural activity. Therefore, the effects of agricultural expansion may vary even further from previous estimates of carbon emissions if a more comprehensive crops scheme were used in the coupled carbon-climate model simulations (Bondeau *et al.* 2007, de Noblet-Ducoudré *et al.* 2004, Smith P. – personal communication).

CHAPTER 5. DISCUSSION AND CONCLUSIONS

In this work I have introduced an interactive dynamic scheme of carbon allocation that redistributes the land use related carbon between direct and deferred carbon pools and calculates the associated emissions in a global carbon-climate model of intermediate complexity. I have also performed a series of transient simulations with this model including the extended dataset of crops and pastures. The results of this research have revealed a range of uncertainties associated with the earlier model-based estimates of the LULCC-related carbon emissions (Betts 2001, Bounoua *et al.* 2002, Forster *et al.* 2007, Leemans *et al.* 2002) which possibly underestimate the magnitude of these emissions and their impact on the carbon cycle and climate because of the underestimated extent of agricultural land as well as the underestimated effects of different agricultural practices. I hope that this study will partly help in resolution of these uncertainties.

5.1 Discussion

The results here suggest that the historical effect of LULCC on the atmospheric CO_2 concentrations in model-based estimates from 1700 to 2000 may be underestimated by up to 30ppm. This is, in part, because the agricultural land in such simulations is typically modeled simply as naturally grown grasses. However, the experiments performed here showed that in fact, neither C3/C4 grasses nor a mixture of the two are fully representative of the agricultural land in the model simulations as both underestimate the level of atmospheric CO_2 concentrations in comparison to the observed level. Instead, crop types, crops phenology and land conversion types (e.g. forest to crops or crops to pastures) need to be included in the model calculations. This task may be accomplished by incorporation of a comprehensive crop model in the UVic ESCM as a future step of model development.

The obtained results here also highlight the importance of including the extent of pastures in the calculations as both pasture land and crop land are restricted for agricultural use and consequently no natural vegetation other than grasses is allowed to grow on these lands. Many simulations to date have included only the effect of crops, which would underestimate LULCC CO_2 emissions (Strassmann *et al.* 2008, Solomon *et al.* 2007). This problem has been resolved within this study and the simulations that included pastures show that pastures contribute up to 14ppm of CO_2 concentration increase simulated by the model. Multiple biogeophysical and biogeochemical effects can induce these increased rates of carbon emissions that created the atmospheric CO_2 concentrations corresponding to the simulation driven by the combined dataset of crops and pastures (see Figure 4.2.2). The most prominent of them would be the positive change in the radiative forcing attributable to the expansion of agricultural land replacing natural forests, release of carbon stored in vegetation and soils, soil erosion, as well as increased soil respiration and decreased natural productivity (see also Table 2.1.1 for reference). It probably worth noting here, that the combination of these effects, as simulated in this study, seems to overcome the cooling effect attributed to the higher albedo of the expanded agricultural land vs.

the lower albedo of the replaced forested land, combined with the associated change in precipitation patterns (Marland *et al.* 2003, Betts *et al.* 2007).

An additional uncertainty may arise from the fact that the process of soil erosion is not included in the calculations. If this information were to be considered in the model then even the simulations which have represented crops as bare ground in this work may be underestimating the associated carbon emissions (Roose *et al.* 2005, Sabine *et al.* 2004). This is because cultivated land is susceptible for erosion even more than usual compacted bare ground and thus more soil carbon may be removed by erosion and heterotrophic respiration (Liu *et al.* 2003, Oost *et al.* 2007, Roehm and Roulet 2003, Yadava and Malanson 2009).

5.2 Experiment limitations

The limiting factors which directly influence these results are: (1) limitation of photosynthesis by water and nutrients (Thornton *et al.* 2007) that was not dynamically included in the model (though a simplified scheme regulating the nutrients accessibility by plants is implemented in the UVic ESCM terrestrial component – Matthews *et al.* 2005a and b); (2) the irrigation, runoff, and soil erosion associated with LULCC which are not included in the simulations; and (3) the land clearing by fire. Consequently, the current experiment was lacking the effects of fertilization of agricultural land, as well as the control of the hydrological cycle over this land. In addition, a comprehensive crops model is essential for comprehensive LULCC modeling, and, therefore (4) the experiments here were limited by the lack of such a model in the analysis. The first and second limitations may cause an overestimate of the carbon sink and carbon fertilization effects, while the third and the fourth may lead to a significant underestimate of land use induced carbon emissions. Synergistically those limitations provide a set of additional arguments in support of the conclusion that the effects of LULCC on carbon cycle and climate may be underestimated. However, the full impact of those limiting factors needs further study as do their implications for estimates of the total human contribution to climate forcing.

5.3 Further research

The improvements made to the model in the current work create an important basis for future research that will ensure an improved level of accuracy in quantifying the net effects of the LULCC on current and future climate while quantifying the strength of the terrestrial carbon sink and foreseeing possible feedbacks to the carbon cycle. Furthermore, based on the obtained results, I see a necessity for further research to be conducted on the biogeochemistry and the biogeophysics of crop types in relation to their climatological aspects as well as in relation to crops/crop-pasture rotations and to other types of land conversions. In addition, in the context of the emissions mitigation strategies, an additional research is required in the areas of reducing uncertainties in biomass estimates, quantifying of land fragmentation and degradation, understanding regional heterogeneities of changes, quantifying drivers and feedbacks between LULCC and climate change and quantifying effects of reforestation as an effective mitigation strategy. Resolution of these uncertainties is probably to result from spatially detailed current databases driven by the satellite data of high spatial resolution, combined with historical reconstructions of land use change and comprehensive model representation of both biogeochemical and biogeophysical effects of crops including their phenology, effects of crop rotations and land transitions, the associated soil erosion, effects of irrigation and fertilization of agricultural lands, and possibly other, yet underestimated, impacts of human induced LULCC on climate.

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APPENDICES

Appendix A. Terrestrial Carbon Stocks

Table 2.2.1A. Estimates of terrestrial carbon stocks (global aggregated values by biome), Source: House et al. 2002

Biome	Area (10^9 ha)		Global Carbon Stocks (PgC)[d]					
			WBGU[a]			RSM[b]IGBP[c]		
	WBGU[a]	RSM[b]	Plants	Soil[d]	Total	Plants	Soil[d]	Total
Tropical forests	1.76	1.75	212	216	428	340	213	553
Temperate forests	1.04	1.04	59	100	159	139[e]	153	292
Boreal forests	1.37	1.37	88[f]	471	559	57	338	395
Tropical savannas & grasslands	2.25	2.76	66	264	330	79	247	326
Temperate grasslands & shrublands	1.25	1.78	9	295	304	23	176	199
Tundra	0.95	0.56	6	121	127	2	115	117
Deserts and semi deserts	4.55[h]	2.77	8	191	199	10	159	169
Croplands	1.6	1.35	3	128	131	4	165	169
Wetlandsg	0.35	–	15	225	240	–	–	–
Total	15.12	14.93[h]	466	2011	2477	654	1567	2221

[a] WBGU (1998): forest data from Dixon *et al.* (1994); other data from Atjay *et al.* (1979)

[b] RSM: Roy, Saugier & Mooney (RSM) 2001. Temperate grassland and mediterranean shrubland categories combined

[c] IGBP-DIS (International Geosphere–Biosphere Programme – Data and Information System) soil carbon layer (Carter & Scholes, 2000) overlaid with DeFries *et al.*, 1995) current vegetation map to give average ecosystem soil carbon

[d] Soil carbon values are for the top 1 m, although stores are also high below this depth

in peatlands and tropical forests
[e] RSM temperate forest estimate is likely to be too high, being based on mature stand density
[f] WBGU boreal forest vegetation estimate is likely to be too high due to high Russian forest density estimates including standing dead biomass
[g] Variations in classification of ecosystems can lead to inconsistencies. In particular, wetlands are not recognized in the RSM classification
[h] Total land area of 14.93 x 109 in RSM includes 1.55 x 109 ha ice cover not listed in this table. In WBGU, ice is included in deserts and semidesterts category.

Appendix B. Land Use Data

Figure 3.2.2B. Transient Climate Change and Potential Croplands of the World in the 21st Century (Adopted from: Xiangming Xiao *et a.l* 1997)

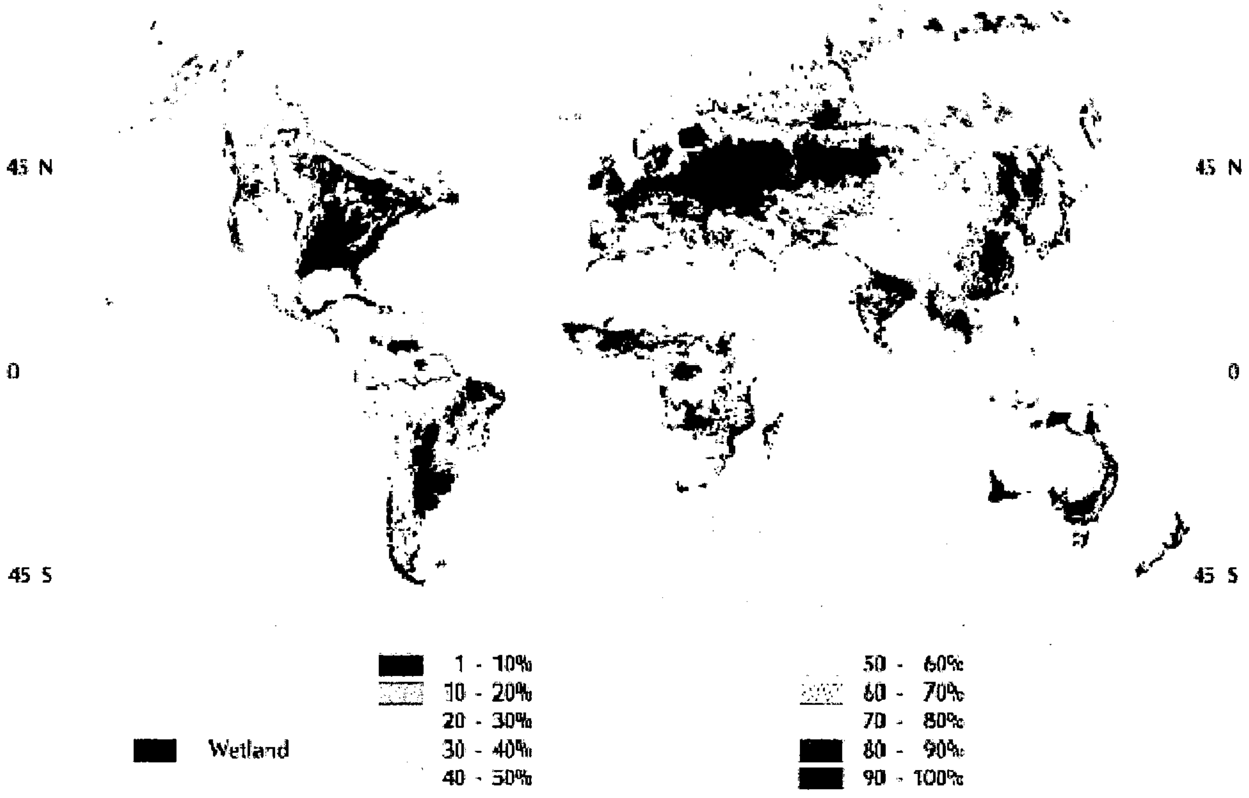
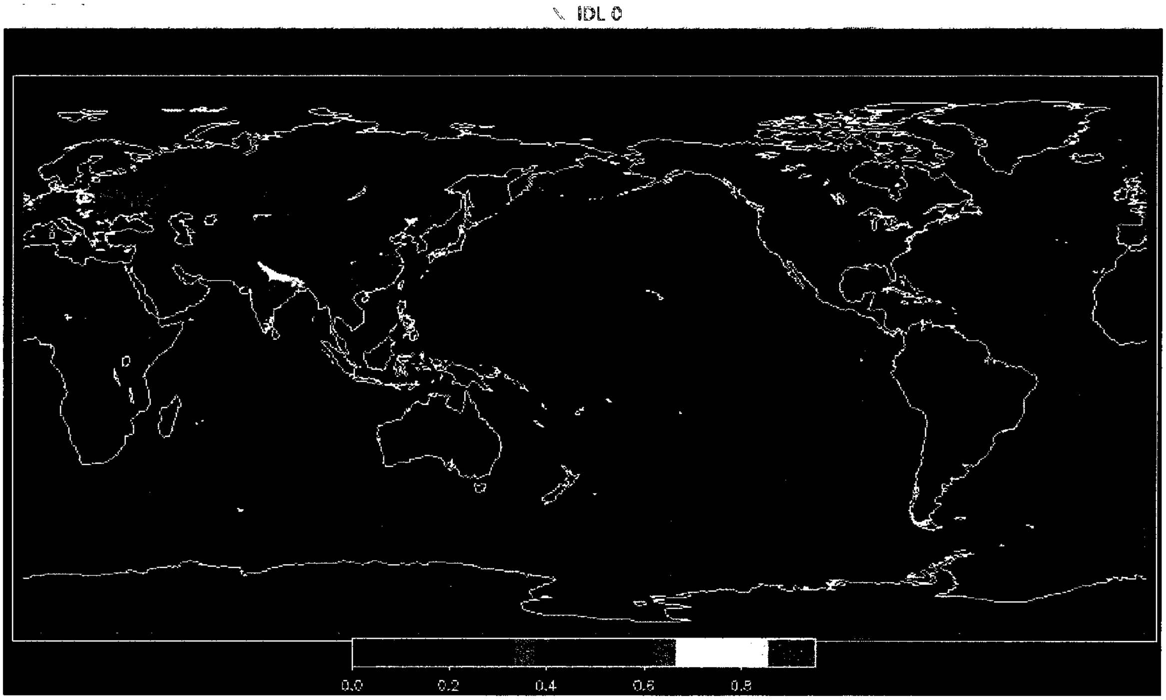
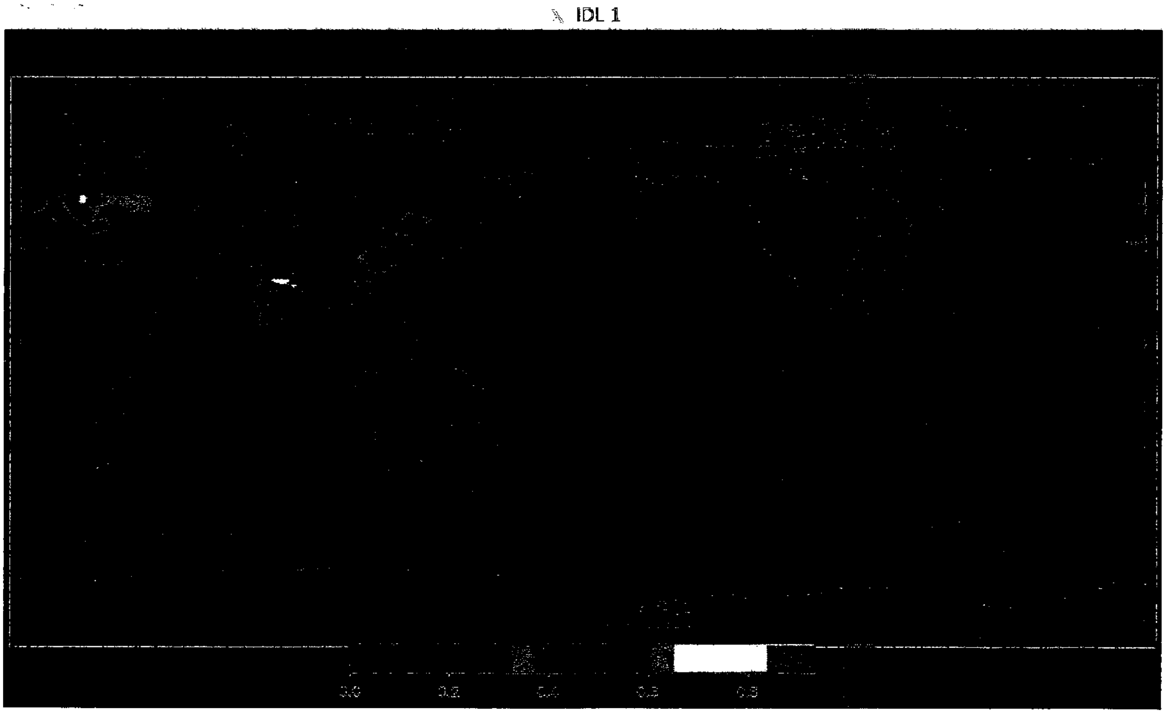


Figure 3.2.3B. Land Use Data (for the year 1700): Plotted (a, c); Normalised (b, d) and Combined Plotted (e).

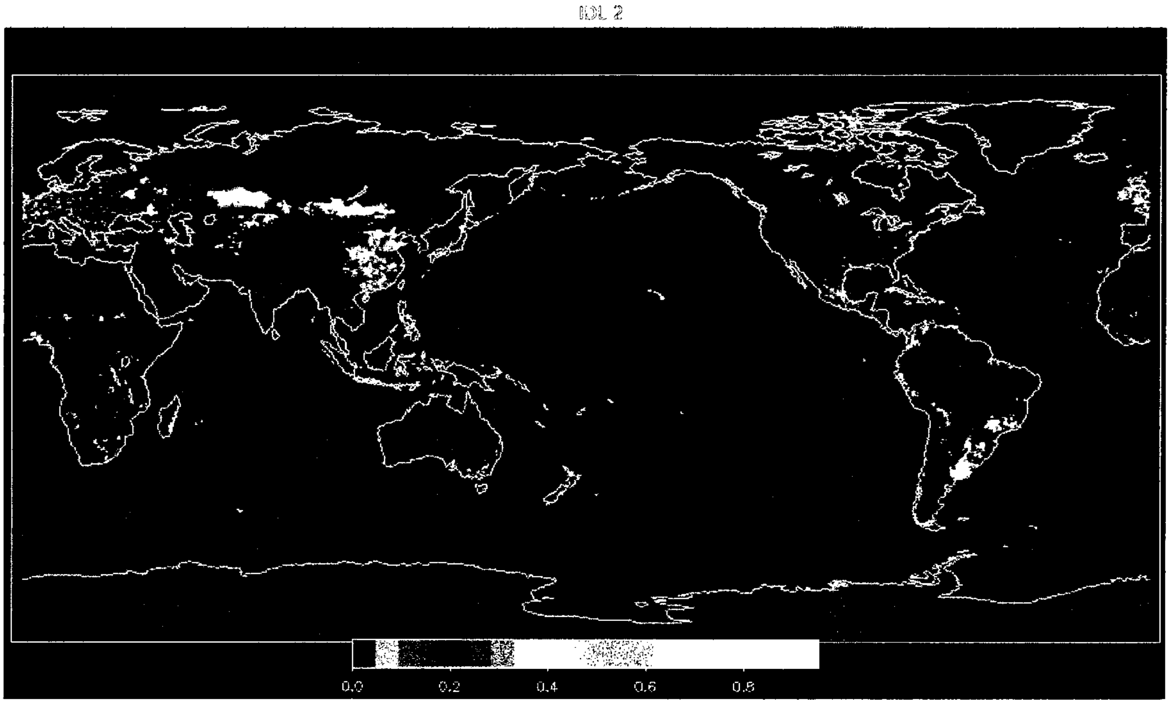
(a) Crops 1700, 5' resolution



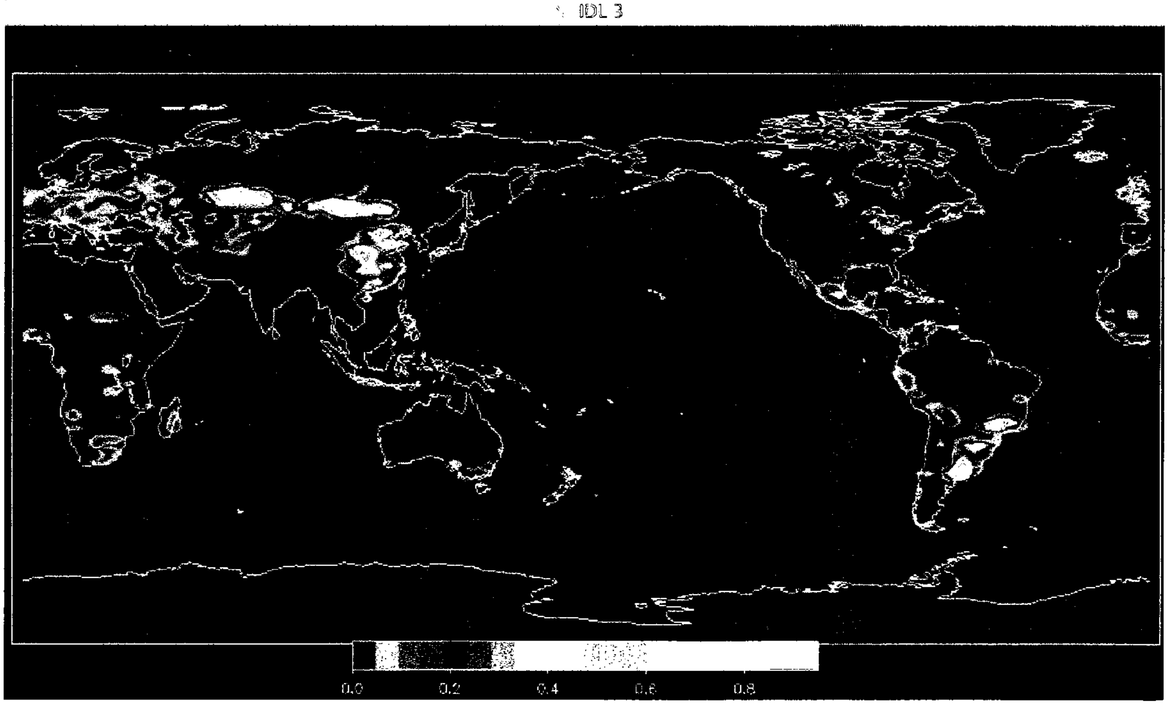
(b) Crops 1700 normalized to the UVic ESCM grid



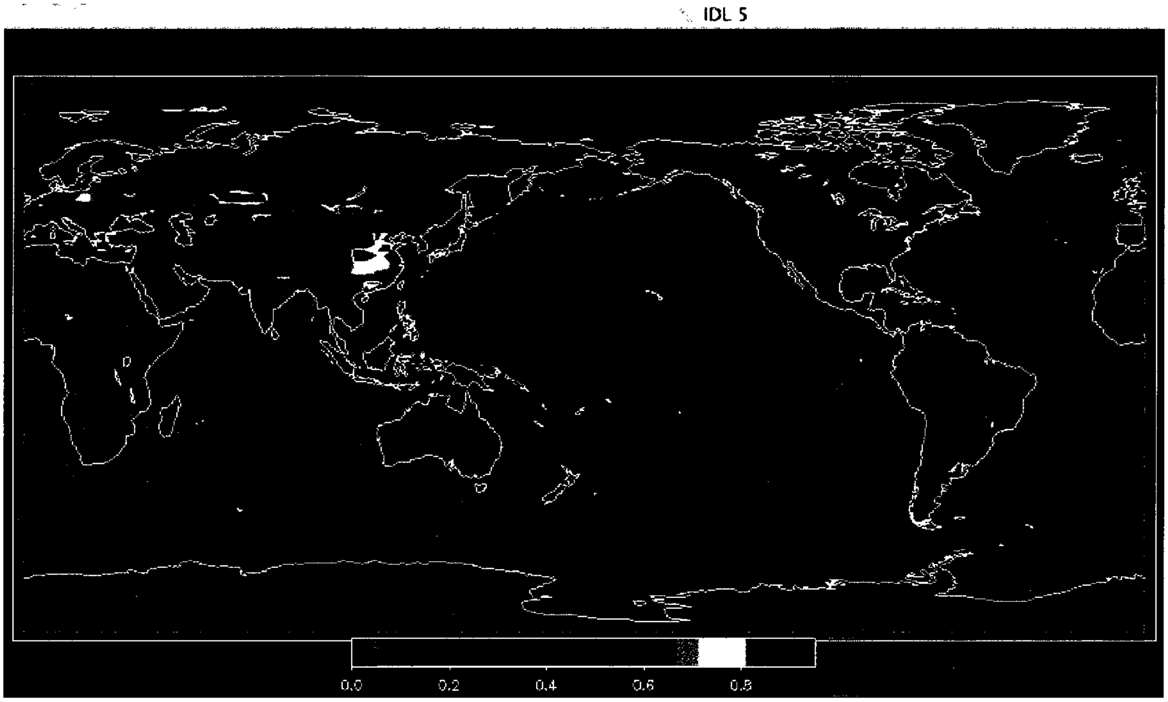
(c) Pasture 1700, 5' resolution



(d) Pasture 1700 normalized to the UVic ESCM grid



(e) Combined normalized dataset of Crops and Pastures (for the year 1700)

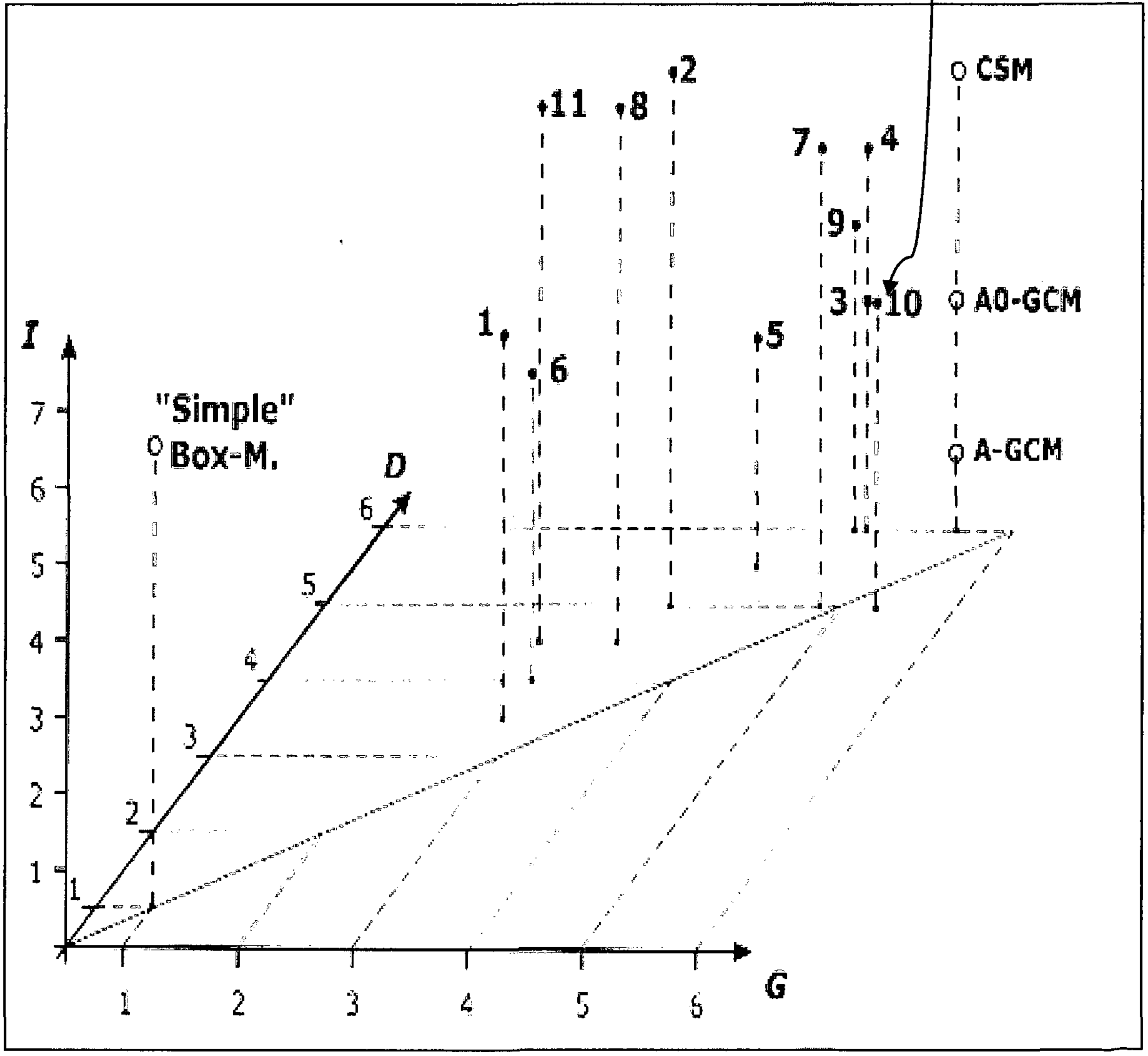


Appendix C. Model Description

Figure 3.3.1C Place of the UVic ESC Model among the other models of intermediate complexity (a), and (b) Pictoral definition of EMICs (Sources: Weaver et al., 2001, Claussen et al., 2002)

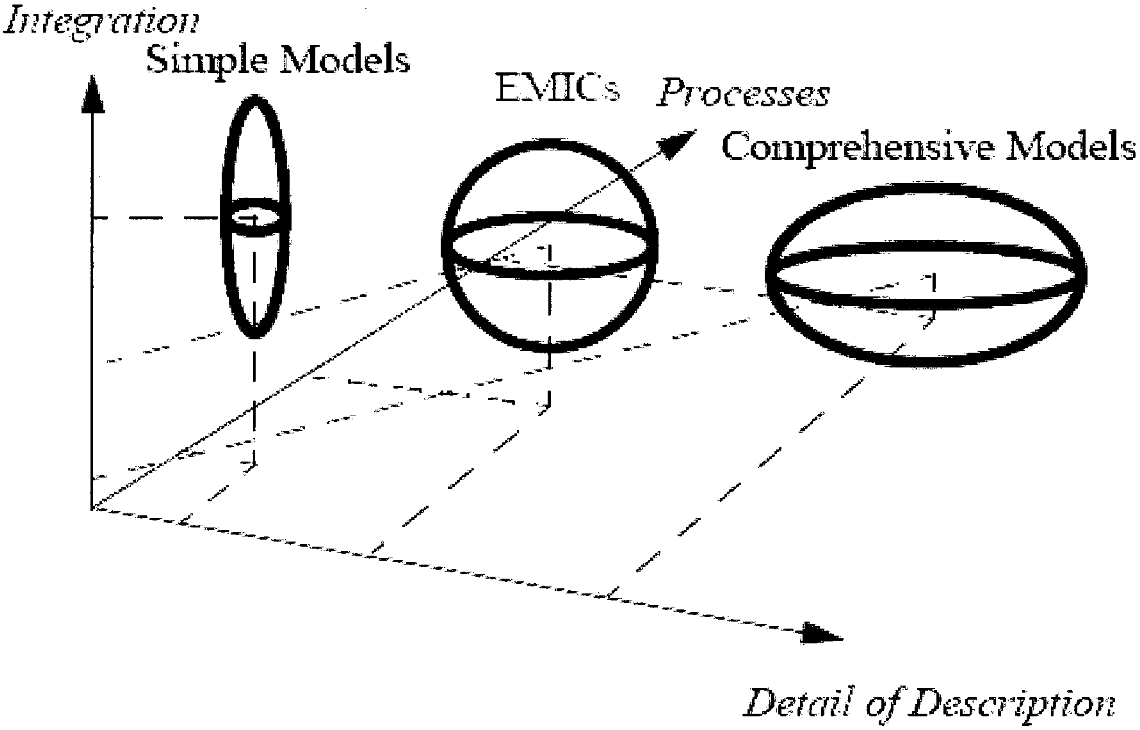
(a)

1. Bern 2.5D
2. CLIMBER-2
3. EcBilt
4. EcBilt-CLIO
5. IAP RAS
6. MPM
7. MIT
8. MoBidiC
9. PUMA
10. UVic ESCM
11. IMAGE 2



(b)

Schematic illustration of the place of Models of Intermediate Complexity (EMICs) in the three-dimensional space of processes, integration, and Details of description, by comparison to simple one-dimensional models and comprehensive Global Circulation Models.



Appendix D. Model Development

In order to explain the details of a new land use carbon reallocation in the model, a comprehensive diagram is provided below (Fig. 3.3.4D, Symbols are

$$\frac{dC}{dt} = C_0 n e^{nt} = k_{HL} C_0 n_{HL} e^{n_{HL} t} + k_{SH} C_0 n_{SH} e^{n_{SH} t} + k_{LN} C_0 n_{LN} e^{n_{LN} t}$$

Emissions from

carbon reallocated to:

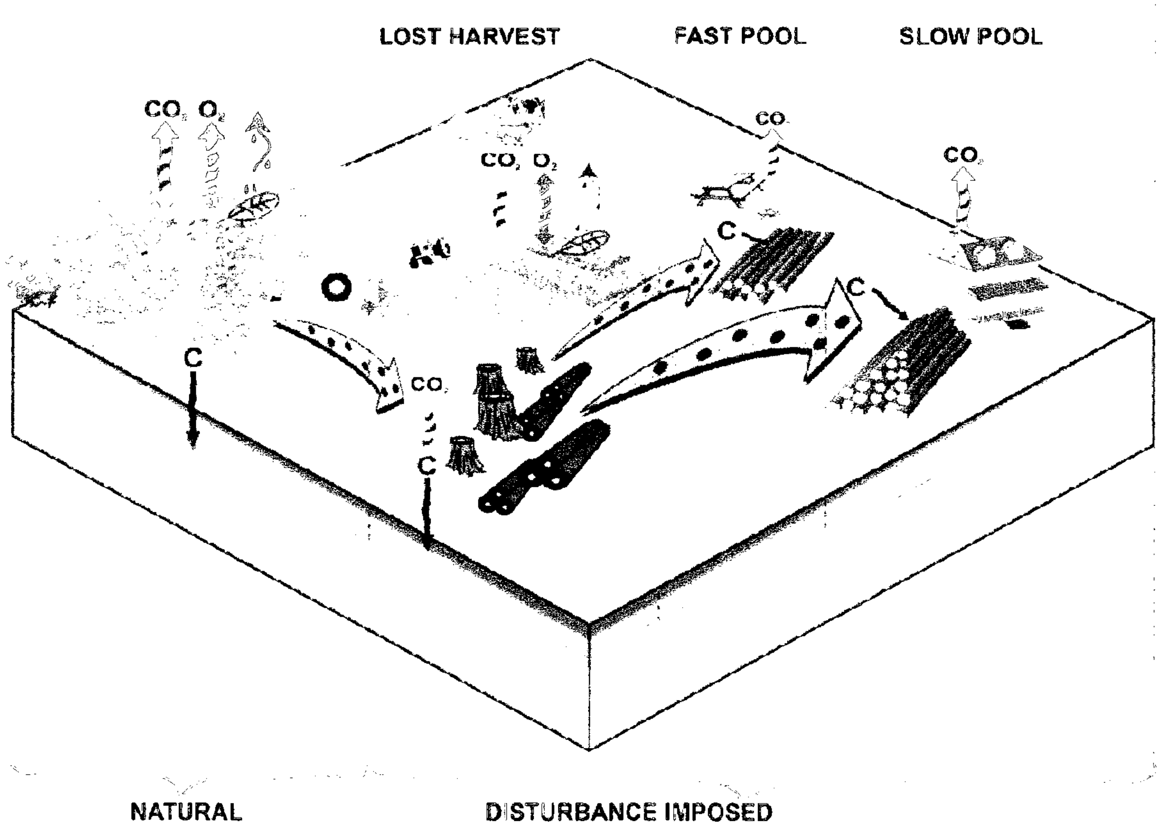


Figure 3.3.4D. Diagram showing carbon reallocation in the modified version of the UVic ESCM

courtesy of the Integration and Application Network (ian.umces.edu/symbols/), University of Maryland Center for Environmental Science). This diagram shows the three ‘decay’ terms of the PDE describing the change in the model vegetation carbon and beneath each of the terms there are respective rate of decay charts and the appropriate symbols giving an idea of the calculated constants of decay as well as the physical meaning of the respective equation terms. The exponential decay constants were calculated using the Euler's solution for exponential decay and assuming the average half-lives of 1 and 10 years for the respective fast and slow wood product carbon pools (Skog *et al.* 2004, Strassman *et al.* 2008). These coefficients were further incorporated in the UVic ESCM v.2.8 as interactive variables, thus allowing simulation of varying wood product half-life's values in order to estimate the sensitivity of the model and/or the climate to this parameter. The scheme is realised in such a way that the amount of carbon equal to the change in the vegetation carbon content is calculated by the coupled to the UVic ESCM version of the DGVM TRIFFID, and at every time step redistributed between the new carbon pools, and then partially returned to the same time step, while the respective part of the 'decayed' wood product carbon is added to the model at the next time step. Thus, the modified version of the model at every time step accounts for the land use carbon immediately burned or otherwise translated to the atmosphere within the first year following deforestation, and also for the decayed part of the carbon previously redistributed to the wood product carbon pools.

Appendix E. Simulations Results

Table 4.1.1E. Simulated global averaged carbon flux from land use change 1900-2000 (KgC/yr and GtC/yr) and Global combined area of agricultural land 1900-2000 (million km^2)

Time, Year	Area of agriculture, 10^6 Km^2	Carbon Flux (BURN)	
		KgC/s	Gt C/yr
1900	1.73244E+13	27279.6035	8.60E+11
1901	1.74091E+13	27388.4023	8.64E+11
1902	1.75175E+13	28764.0996	9.07E+11
1903	1.76485E+13	28916.9004	9.12E+11
1904	1.77779E+13	29168.5391	9.20E+11
1905	1.79102E+13	32147.7832	1.01E+12
1906	1.80424E+13	29926.2695	9.44E+11
1907	1.81701E+13	30246.3027	9.54E+11
1908	1.82961E+13	30504.8652	9.62E+11
1909	1.84246E+13	31065.3789	9.80E+11
1910	1.85533E+13	31140.0332	9.82E+11
1911	1.86785E+13	33846.5117	1.07E+12
1912	1.88027E+13	31604.3887	9.97E+11
1913	1.89264E+13	31875.6816	1.01E+12
1914	1.90515E+13	31841.8496	1.00E+12
1915	1.91848E+13	32698.0527	1.03E+12
1916	1.9322E+13	32818.6172	1.03E+12
1917	1.94441E+13	35388.7227	1.12E+12
1918	1.95539E+13	32849.418	1.04E+12
1919	1.96608E+13	32945.6836	1.04E+12
1920	1.97677E+13	33137.668	1.05E+12

1921	1.98784E+13	33395.3398	1.05E+12
1922	2.00108E+13	34047.0117	1.07E+12
1923	2.01596E+13	37014.1094	1.17E+12
1924	2.03063E+13	34754.9375	1.10E+12
1925	2.04529E+13	34802.832	1.10E+12
1926	2.05988E+13	35317.6133	1.11E+12
1927	2.07462E+13	35310.1016	1.11E+12
1928	2.08945E+13	35662.6055	1.12E+12
1929	2.10422E+13	38629.2617	1.22E+12
1930	2.11923E+13	36552.0625	1.15E+12
1931	2.13314E+13	36223.3633	1.14E+12
1932	2.14501E+13	36153.5742	1.14E+12
1933	2.15611E+13	36166.8555	1.14E+12
1934	2.16679E+13	36271.0664	1.14E+12
1935	2.1775E+13	39410.8438	1.24E+12
1936	2.18824E+13	36644.8828	1.16E+12
1937	2.20051E+13	37052.582	1.17E+12
1938	2.21321E+13	37304.543	1.18E+12
1939	2.22349E+13	37341.5781	1.18E+12
1940	2.23421E+13	37613.2383	1.19E+12
1941	2.24533E+13	40919.8828	1.29E+12
1942	2.25325E+13	37965.5391	1.20E+12
1943	2.26E+13	38166.2891	1.20E+12
1944	2.26858E+13	38407.2422	1.21E+12
1945	2.27608E+13	38518.2109	1.21E+12
1946	2.28248E+13	38699.4336	1.22E+12
1947	2.2929E+13	42362.2813	1.34E+12
1948	2.30291E+13	39300.7461	1.24E+12

1949	2.31099E+13	39523.3359	1.25E+12
1950	2.31984E+13	39703.5078	1.25E+12
1951	2.3293E+13	39764.3281	1.25E+12
1952	2.34307E+13	40751.0391	1.29E+12
1953	2.36467E+13	44830.8516	1.41E+12
1954	2.3877E+13	41903.0977	1.32E+12
1955	2.40579E+13	42337.4883	1.34E+12
1956	2.42452E+13	42927.1953	1.35E+12
1957	2.44657E+13	43910.8594	1.38E+12
1958	2.46851E+13	44073.8867	1.39E+12
1959	2.48641E+13	47983.2969	1.51E+12
1960	2.49805E+13	44704.9414	1.41E+12
1961	2.50646E+13	45201.6211	1.43E+12
1962	2.516E+13	45593.0586	1.44E+12
1963	2.52487E+13	45142.8711	1.42E+12
1964	2.53201E+13	45346.8359	1.43E+12
1965	2.53865E+13	49498.6016	1.56E+12
1966	2.54591E+13	46088.8008	1.45E+12
1967	2.55371E+13	46369.6367	1.46E+12
1968	2.56176E+13	46674.707	1.47E+12
1969	2.57069E+13	47132.6133	1.49E+12
1970	2.58009E+13	47484.1719	1.50E+12
1971	2.58529E+13	51857.9453	1.64E+12
1972	2.58438E+13	47130.1445	1.49E+12
1973	2.58585E+13	47789.3125	1.51E+12
1974	2.58976E+13	48152.5859	1.52E+12
1975	2.59247E+13	48771.9414	1.54E+12
1976	2.59451E+13	49088.8906	1.55E+12

1977	2.59676E+13	54297.5156	1.71E+12
1978	2.60061E+13	50787.3516	1.60E+12
1979	2.60458E+13	51065.5469	1.61E+12
1980	2.60996E+13	51351.9805	1.62E+12
1981	2.6128E+13	51745.3008	1.63E+12
1982	2.61315E+13	51331.2188	1.62E+12
1983	2.61379E+13	55723.3125	1.76E+12
1984	2.61282E+13	52046.1836	1.64E+12
1985	2.61233E+13	52114.6133	1.64E+12
1986	2.61308E+13	53503.1719	1.69E+12
1987	2.61381E+13	52750.6641	1.66E+12
1988	2.61442E+13	52749.4492	1.66E+12
1989	2.61481E+13	56982.7305	1.80E+12
1990	2.6134E+13	51911.6484	1.64E+12
1991	2.61066E+13	52137.8945	1.64E+12
1992	2.61085E+13	54379.7578	1.71E+12
1993	2.61393E+13	55938.5234	1.76E+12
1994	2.61702E+13	57886.6211	1.83E+12
1995	2.6201E+13	64177.1602	2.02E+12
1996	2.62319E+13	60726.4883	1.92E+12
1997	2.63034E+13	59432.2734	1.87E+12
1998	2.64166E+13	59887.793	1.89E+12
1999	2.65297E+13	60633.1914	1.91E+12
2000	2.66429E+13	61395.4141	1.94E+12

Table 4.2.1E. Simulated CO_2 concentrations (ppm) including and not including the intermediate wood product carbon pools

Time (Year)	CO_2 concentrations (ppm)		
	Wood Pools	No Wood Pools	CO_2 Data
1960	309.224701	311.5172	316.910004
1961	309.942719	312.2712	317.630005
1962	310.663239	313.0245	318.459991
1963	311.397247	313.7827	319.019989
1964	312.167877	314.5691	319.519989
1965	312.979889	315.4065	320.089996
1966	313.83548	316.2883	321.339996
1967	314.72525	317.2084	322.130005
1968	315.644348	318.1582	323.109985
1969	316.61319	319.1563	324.600006
1970	317.65509	320.2281	325.649994
1971	318.770477	321.3696	326.320007
1972	319.917572	322.5303	327.519989
1973	321.097656	323.7237	329.609985
1974	322.328156	324.9838	330.290009
1975	323.545929	326.2313	331.160004
1976	324.749207	327.4676	332.179993
1977	326.014709	328.7702	333.880005
1978	327.318909	330.1269	335.519989
1979	328.638611	331.4928	336.890015
1980	330.015747	332.9103	338.670013

1981	331.344482	334.2813	339.950012
1982	332.58963	335.5604	341.089996
1983	333.786377	336.7759	342.75
1984	334.980194	337.998	344.440002
1985	336.221497	339.2686	345.859985
1986	337.523926	340.6197	347.140015
1987	338.873505	342.0159	348.98999
1988	340.259674	343.4235	351.440002
1989	341.698608	344.8765	352.940002
1990	343.15567	346.3402	354.190002
1991	344.608337	347.7943	355.619995
1992	346.072418	349.2961	356.359985
1993	347.514496	350.8152	357.100006
1994	348.972321	352.3723	358.859985
1995	350.487152	353.989	360.899994
1996	352.064209	355.6701	362.579987
1997	353.672821	357.3451	363.839996
1998	355.279419	358.9919	366.579987
1999	356.852783	360.6167	368.299988
2000	358.40152	362.2273	369.470001
2001	360.051971	363.9106	371.029999
2002	361.743774	365.6065	373.070007
2003	363.473297	367.3487	
2004	365.247437	369.1418	
2005	367.062592	370.9793	
2006	368.919403	372.8624	

2007	370.817444	374.7892	
2008	372.75943	376.7693	
2009	374.744141	378.7928	
2010	376.77533	380.869	

Table 4.2.2E. Simulated global average surface air temperature SAT(K) with extreme and real values of the burnt fraction of LULCC (BF, %)

Time (Year)	Temperature (SAT, K)		
	BF=0.0	BF=0.74	BF=1.0
1950	286.299866	286.30896	286.31073
1951	286.302917	286.312775	286.315308
1952	286.304932	286.313263	286.318176
1953	286.309418	286.317505	286.32196
1954	286.312744	286.319733	286.323792
1955	286.317383	286.326233	286.33017
1956	286.318756	286.328613	286.331177
1957	286.322754	286.332733	286.334961
1958	286.3284	286.334778	286.339233
1959	286.33197	286.339081	286.341217
1960	286.33548	286.346069	286.347382
1961	286.340088	286.350159	286.351868
1962	286.345123	286.355225	286.358673
1963	286.351562	286.362305	286.36496
1964	286.355164	286.366577	286.367554
1965	286.361847	286.372375	286.372467
1966	286.364502	286.376862	286.376526

1967	286.371429	286.381683	286.383484
1968	286.377441	286.387207	286.390686
1969	286.385529	286.395691	286.398529
1970	286.390747	286.402222	286.406189
1971	286.398834	286.40741	286.412537
1972	286.407715	286.416809	286.41748
1973	286.414337	286.426056	286.426331
1974	286.422119	286.433136	286.433411
1975	286.432404	286.44223	286.443542
1976	286.440094	286.448883	286.450867
1977	286.452026	286.461487	286.462463
1978	286.458893	286.469849	286.469299
1979	286.468506	286.479279	286.481049
1980	286.476624	286.486969	286.4888
1981	286.488342	286.499664	286.501404
1982	286.496857	286.509583	286.511017
1983	286.508484	286.51709	286.521606
1984	286.515015	286.525024	286.528778
1985	286.527893	286.539276	286.540802
1986	286.534882	286.544373	286.548615
1987	286.548553	286.556976	286.55835
1988	286.557098	286.567139	286.568756
1989	286.568054	286.578888	286.580383
1990	286.579102	286.588989	286.590271
1991	286.588074	286.597656	286.599274
1992	286.597992	286.610321	286.610504
1993	286.609344	286.620575	286.62207
1994	286.623138	286.633179	286.632904
1995	286.633118	286.643677	286.646576
1996	286.645905	286.656464	286.657898

1997	286.657166	286.665192	286.667603
1998	286.670654	286.67923	286.68161
1999	286.679718	286.689514	286.691406
2000	286.692505	286.699585	286.703094
2001	286.705444	286.716705	286.717896
2002	286.71582	286.726868	286.72818

Table 4.2.3E. Simulated global averaged CO_2 concentrations (ppm) for crops modeled as bare land, C3/C4 grasses, C3+C4 grasses; CO_2 data; No crops (simulation with fossil fuel emissions only) (part a and b)

(a)

Model setup	**Total change in CO_2 concentrations from 1700 to 2000 (ppm)**
Crops (C3+C4)	69.956
C3	69.759
No crops	65.517
Crops+Pastures (C3+C4)	79.704
C4	85.252
Bare Land	108.732
CO_2 Data	92.27

(b)

Time (Year)	**Global averaged CO_2 concentrations (ppm)**					
	C3	**No crops**	**C3 + C4**	**C4**	**Bare Land**	**CO_2 Data**
1950	294.74	297.81	297.81	303.11	308.46	327.52
1951	295.13	298.23	298.16	303.55	308.90	328.05
1952	295.58	298.69	298.55	304.04	309.39	328.62

1953	296.04	299.14	298.94	304.55	309.90	329.22
1954	296.51	299.62	299.34	305.07	310.43	329.86
1955	296.99	300.11	299.75	305.60	310.98	330.55
1956	297.52	300.67	300.21	306.18	311.59	331.31
1957	298.10	301.26	300.71	306.81	312.25	332.15
1958	298.69	301.88	301.23	307.47	312.94	333.06
1959	299.29	302.50	301.76	308.13	313.65	334.01
1960	299.92	303.14	302.32	308.82	314.39	335.00
1961	300.56	303.80	302.91	309.54	315.14	336.02
1962	301.20	304.46	303.49	310.26	315.90	337.07
1963	301.85	305.13	304.09	311.00	316.67	338.13
1964	302.54	305.83	304.73	311.77	317.47	339.19
1965	303.27	306.56	305.41	312.59	318.31	340.26
1966	304.03	307.34	306.13	313.45	319.18	341.34
1967	304.83	308.15	306.89	314.34	320.09	342.43
1968	305.65	308.97	307.68	315.27	321.02	343.53
1969	306.53	309.84	308.51	316.24	321.98	344.68
1970	307.47	310.78	309.40	317.28	323.02	345.88
1971	308.48	311.80	310.36	318.39	324.13	347.15
1972	309.55	312.84	311.36	319.54	325.26	348.41
1973	310.67	313.90	312.40	320.72	326.42	349.67
1974	311.84	315.02	313.48	321.96	327.61	350.95
1975	312.98	316.10	314.54	323.18	328.79	352.19
1976	314.11	317.15	315.58	324.38	329.95	353.38
1977	315.31	318.28	316.67	325.64	331.17	354.62
1978	316.54	319.46	317.80	326.94	332.45	355.89
1979	317.79	320.65	318.94	328.27	333.73	357.19
1980	319.08	321.89	320.12	329.65	335.08	358.56
1981	320.33	323.06	321.26	330.99	336.37	359.87
1982	321.47	324.15	322.32	332.24	337.57	361.10

1983	322.58	325.17	323.33	333.44	338.72	362.26
1984	323.69	326.18	324.34	334.64	339.86	363.40
1985	324.84	327.25	325.39	335.88	341.05	364.60
1986	326.06	328.38	326.50	337.19	342.30	365.84
1987	327.31	329.55	327.66	338.55	343.61	367.13
1988	328.60	330.77	328.85	339.94	344.96	368.46
1989	329.94	332.05	330.10	341.38	346.35	369.86
1990	331.29	333.34	331.38	342.84	347.74	371.28
1991	332.64	334.62	332.67	344.30	349.10	372.68
1992	333.97	335.90	333.96	345.76	350.45	374.06
1993	335.26	337.17	335.19	347.21	351.79	375.41
1994	336.54	338.46	336.42	348.67	353.16	376.76
1995	337.86	339.83	337.68	350.19	354.61	378.18
1996	339.23	341.28	338.99	351.76	356.16	379.69
1997	340.64	342.76	340.33	353.37	357.77	381.27
1998	342.07	344.23	341.70	354.97	359.40	382.90
1999	343.46	345.65	343.03	356.54	361.00	384.54
2000	344.83	347.04	344.34	358.09	362.58	386.17

Appendix F. Supporting Materials

Table 5.0.1F Units and Conversions

Abbreviation	Units
1 Mt	1 Megatonne = 1 million tonnes = 1 Tg = 10^{12} gramme
1 Gt	1 Gigatonne = 1000 Mt = 10^{9} tonnes = 1 Pg = 10^{15} gramme
1 Pg	Petagramme = 1 Gt
1 GtC	1 Gigatonne Carbon
1 tC	1Tonne Carbon = 3.67 tCO_2
1 tCO_2	0.27 tC