A. Scientific/Technological methodology and associated work plan

A.1 Overall strategy and general description

The overall design of the project is to achieve full consistency in data streams and methodologies, from local to regional and European scale. Observational evidence of ecosystem C and **CO_2, N_2O and CH_4** budgets and response to changing drivers will be used to validate, calibrate and improve models. Uncertainties will be systematically accessed via a range of standardized tools and fully propagated across scales and integration steps. Together with improved historical data and projections of natural and anthropogenic drivers and socio-economic pressures at regional and European scale, this allows an integrated analysis of the C and **CO_2, N_2O and CH_4** budget in European terrestrial ecosystems, the annual to decadal variability and future vulnerability based on much improved knowledge.

The work flow contains the following elements, which are reflected in Work Packages (cf. Pert diagram):

Variability in drivers (WP1): We will compile in harmonized space and time resolution **long-term statistical and georeferenced data and remote sensing products on natural and human drivers** that document changes in climate, land use, land management and N deposition, and in lateral C flows. Drivers also include socio-economic data and agricultural and land use related policies and international trade information as a basis for plausible projections consistent with past and present patterns. All driver fields will be made available on at least a **0.25x0.25° grid for EU27+ (27 member states of the European Union plus Switzerland),** which is the smallest common grid size for all variables, and at finer spatial resolution where possible / appropriate.

Improved observational evidence at ecosystem level of C and **CO_2, N_2O and CH_4** budgets and response to changing drivers, **improved understanding of critical processes (WP2)**: **Process studies** that utilize **long-term carbon and CO_2, N_2O and CH_4 observations, ecosystem manipulations, factorial experiments and gradients of climate, land use and management intensity** to elucidate the reaction of carbon and GHG processes to changes in anthropogenic and natural drivers. A focus will be on the response of soil organic carbon and woody biomass and where relevant, N_2O and CH_4 fluxes, to changes in anthropogenic drivers encompassing past and present land use, management and N deposition. We build on existing European experiments, organise them into a network with a joint central database, and carry out harmonized additional cross-site measurements to achieve the critical mass of information for model evaluation and parameterization.

Regional integration of GHG flux observations, vertical and lateral C fluxes and driver fields (WP3): Six data-rich pilot regions were selected across a wide range of climate zones, biomes, land uses, and socio-economic frame conditions, to quantify lateral C transport at the level of farm budgets and region, and integrate information at the relevant scale for land use decisions. The availability of high-quality data on drivers and **CO_2, N_2O and CH_4** fluxes makes the regions an ideal test bed for models (WP4, WP5).

For attribution and **CO_2, N_2O and CH_4** budget calculations at regional and European level we will employ three **types of models** and thus combine the respective strengths. **Advanced multivariate statistical data analysis** (fuzzy logic, regression trees, artificial neural networks) serve to derive response functions of C and **CO_2, N_2O and CH_4** fluxes to changing drivers from the observations (WP2, WP4) and may **detect unknowns and surprises** in ecosystem response to complex **factor combinations**. State-of-the-art **sectoral models for forests, croplands and grasslands with detailed representation of land management** disentangle the impact of the usually complex interactions between past and present changes in drivers, and the interactions among the various types of anthropogenic drivers for CO_2, CH_4 and N_2O (WP4). **Generic ecosystem models, containing all ecosystem types and detailed ecosystem physiology, but only a coarse represesentation of land management** have their strength in quantifying the European C balance and effects of climate variability and land use change (WP5). All models will be subject to systematic uncertainty analysis with common procedures provided by WP7.

The models, with their quantified uncertainties in ecosystem response, will be used for estimating the future vulnerability of ecosystem C stocks and GHG emissions to changing drivers in the next decades (WP6). We will run **scenarios** 1) **consistent with the socio-economic scenarios for IPCC AR5** for assessing likely decadal trends in C and **CO_2, N_2O and CH_4** budgets, 2) with **extreme factor combinations for assessing risks** for C sources and higher **CO_2, N_2O and CH_4** emissions, and 3) with **dynamic change in land use and management with feedback to European policies and global bioenergy and timber markets**.

A.2 Detailed work plan by Work package

WP1 Quantification of spatial and temporal variability of the main factors driving GHG fluxes

The objective of WP1 is to **provide standardized gridded fields of natural and anthropogenic drivers for EU27+** which are then used both as input **to modelling and data analysis** in WP2, WP4, WP5 and WP6 via the *GHG-Europe* database (WP7). WP1 will ensure that the gridded fields are harmonized with the ongoing projects *CC-TAME* and *CARBO-Extreme.* The main properties of the driver fields are summarized in Table 1.

Table 1: Characteristics of driver fields provided by WP 1

Driver field	Temporal extent past; scenarios	Temporal resolution	Comment
1. Natural drivers Soil properties Air temperature Air humidity Precipitation Incoming radiation diffuse Incoming radiation direct	 Static 1900-2010; 1950-2100 1900-2010; 1950-2100 1900-2010; 1950-2100 1860-2010; 1950-2100 1860-2010; 1950-2100	 Static 6 hourly 6 Hourly 6 Hourly 6 hourly 6 hourly	 ERA interim data Two separate, internally consistent datasets for all natural driver fields
Atmospheric CO_2 concentration	1860-2010; 1950-2100	Annual	IPCC scenarios
2. Nitrogen deposition (oxidized / reduced N)	1900-2006 (2010)	Monthly	Past: EMEP and models (Dentener et al. 2006); Scenarios from RAINS
3. Land-use	1900-2010; -2100	Yearly	Includes land use change; future from WP6 economic scenarios
• **4. Forest management** By forest type: • Age class distrib. • Harvest	1950-2008; -2100	Yearly	Downscaled forest inventories; inter- and extrapolation with EFISCEN model
5. Agri. management • N fert. quantity • N fert. type • Crop rotations • Manure appl. • Tillage • Grazing intensity • Cutting frequency	1900-2010;-2100	Yearly	Downscaled census data and expert rules Crop rotation simulator from NitroEurope-IP Future from WP6 economic scenarios
6. Socio-economic drivers and pressures • Population density • GDP density	1950-2008; -2100	Annual	EUROSTAT, National Sources, OECD, Scientific literature, Industry sources. Future in accordance with scenarios for IPCC AR5

We have identified six different types of drivers that need to be treated in appropriate tasks: **1. natural drivers: soil properties, climate parameters (Task 1.1), 2. nitrogen deposition (Task 1.2), 3. land use change (Task 1.3), 4. forest management practices and dynamic age class distribution (Task 1.4), 5. agricultural management practices (Task 1.5), and 6. general anthropogenic drivers describing the socio-economic and policy environment (Task 1.6)**.

All drivers will be made available on a **0.25 x 0.25° grid for EU27+,** which is the smallest common grid size for all variables. **Sub-grid heterogeneity is reflected via a tiling approach** (pixel fractions are assigned to certain properties, e.g. land-use type), such that the information from high-resolution sources can be included. For simulations from past to present, the respective **driver fields** will be assembled for the **period (1860-)1900-2010**, while **scenario datasets** will be developed **for the period (1950)-2010-2050-(2100).** Uncertainty in the past to present driver fields will be assessed using protocols and tools from Task 7.2.

Specific drivers of interannual variability for hotspot ecosystems in WP2 that cannot be used in models of WP4 and WP5 are included in WP2: peat properties and water management in peat soils;

fires in Mediterranean shrublands. WP3 produces similar driver fields for six regions on a high resolution grid (typically 1 km x 1 km) or in fully spatially explicit geoinformation system, whatever is available. In Task 3.4, fields from WP1 are compared against the high resolution fields from WP3 to quantify uncertainties in scale.

WP2 Quantitative understanding of the response and vulnerability of ecosystem C and GHG fluxes to changes in external drivers

The goal of WP2 is to provide full C and CO_2, N_2O and CH_4 budgets of European major ecosystem types at annual to decadal time scales and to quantify the response and vulnerability of terrestrial ecosystems to anthropogenic and natural drivers focusing on critical processes for CO_2, N_2O and CH_4 fluxes based on best available observational evidence.

The European terrestrial C and GHG budget is dominated by large fluxes on small areas (**hot spots and hot moments**): managed peatlands (CO_2, N_2O, CH_4) and land use change areas (CO_2). The uncertainty in local to continental scale GHG budgets is dominated by **unknowns in small GHG fluxes over large areas**: changes in forest and agricultural management (CO_2, N_2O), and extensively used and abandoned ecosystems where a large share of the European C sink is likely to be located: e.g. Eastern European forests and Mediterranean shrublands (mainly CO_2).

Anthropogenic drivers play a major role for GHG fluxes and C pools in European terrestrial ecosystems since 95% of European ecosystems are managed in agricultural and forestry production systems. WP2 will focus on critical processes selected by the following **criteria**: 1) Expected **high impact** on **CO_2, N_2O and CH_4** fluxes and C stocks, 2) **knowledge gaps** due to missing data, assessments and synthesis on European scale, 3) **inadequate representation in models** which needs to be improved with additional knowledge and data (for WP4 and 5).

WP 2 follows a **three step approach** in each Task:

1. **Data collection and synthesis of data and knowledge**: Starting from a review of existing literature, the authors of published **CO_2, N_2O and CH_4** measurements in European ecosystems, and data owners in ongoing national and EU projects such as *CarboEurope-IP* and *NitroEurope-IP* have been contacted in the proposal preparation phase. Many have already agreed to contribute their original measured data and explanatory information about site properties, natural and anthropogenic drivers to a central database. In return, data owners will obtain access to the project database according to the project data policy. The involvement of key experts will aid in harmonizing data and information and will be invited to synthesis workshops. Additional data will be accessed via SOMNET, via compilation of unpublished data from long-term soil monitoring networks, and long-term experiments and from measurements made in WP3.
2. **Additional measurements** will be made of missing or inconsistent explanatory variables, of missing gas species for a complete ecosystem **CO_2, N_2O and CH_4** budget and in under-sampled ecosystems and management systems of existing long term experiments and monitoring sites. Observations will include CO_2, CH_4, N_2O at ecosystem scale wherever relevant. Observations will also be expanded in under-sampled regions and ecosystems: Eastern European forests and land use changes, and Mediterranean shrublands including revegetation and devegetation. We will resample past N deposition experiments in forests to trace the long-term fate of nitrogen and its long-term effect on forest soil C turnover. We will also resample a wide range of land use change experiments to a range of depths of equivalent soil mass, including the subsoil, to overcome inconsistencies and incompleteness in the existing data. These efforts will be amended by measurements made in WP3.
3. **Evidence-driven attribution** of changes in C stocks and **CO_2, N_2O and CH_4** fluxes in terrestrial ecosystems to the investigated natural and anthropogenic drivers: Ecosystem- and region-specific **response functions** will be derived from the collected data via statistical data mining methods, fuzzy logic based modelling and the development of driver-response algorithms based on simple process representation in models from WP4 and WP5. Specific models for peatland and shrubland ecosystems will be improved. We will assess in detail the **vulnerability** of

C stocks in **tree biomass** to change in forest management, the vulnerability of C stocks in **peat soils** to seasonal water management and land use, and the vulnerability of C stocks in **mineral soils** to changes in land use and management.

Data and data synthesis will be provided in annual updates for model evaluation in WP4 and WP5 so that progress in process understanding can progressively feed in model improvement.

Following the criteria above WP2 focuses on six GHG processes representing hotspots of GHG emissions, hot moments of GHG changes and of uncertainty in the European GHG budget: **Managed and natural peatlands at site and catchment scale** will be studied in **Task 2.1**. Peatland management and exploration by drainage, agricultural use and peat extraction have turned pristine peatland GHG sinks into sources. On the other hand, the restoration of degraded peatlands does not always reduce GHG emissions depending on hydrological regimes, fertilization status of the peatlands, climate and vegetation type. In many European countries nationally-funded projects have been set up to investigate peatland GHG fluxes and their drivers. These scattered data and knowledge will be brought together to derive generalised response functions of peatland **CO_2, N_2O and CH_4 fluxes** to natural and anthropogenic drivers such as land management with drainage and climate variability. Many European research groups already agreed to contribute data on CO_2, CH_4 and N_2O fluxes in peatlands to the GHG-Europe data (see Table 1.1b and Fig 2b). Criteria for the site selection:

- complete coverage of the peatland extension over whole Europe
- representative coverage of the dominating peatland-, vegetation- and landuse-types
- GHG-exchange measurements: at least 1 year flux-data for CO2, CH4 or N2O
- willingness of the PI´s to share and analyze the data, specifically in terms of dynamics, management impacts, interannual variability and modelling comparisons

Additionally a large database was built up from an intensive review of published fluxes from European peatlands. These data will be included in the peatland-synthesis activities.

Table 2: Confirmed peatland flux sites included in the synthesis work of GHG-Europe

Country	**Site code in the map**	**Site name**	**Contact person who is confirmed the participation with site data**	**Institution**
Ireland	1	Bellacorick	David Wilson	University College Dublin
	2	Turraun	David Wilson	University College Dublin
	3	Glencar	Anna Laine	Metla
United Kingdom	4	Forsinand	Mark Sutton	CEH
	5	Auchencorth	Mark Sutton	CEH
	6	Moorhouse	Mark Sutton	CEH
	7	Conway	Mark Sutton	CEH
Netherlands	8	Horstermeer	Han Dolman	VUA
France	9	Frasne	Fatima Lagoun	Universités Orléans
Denmark	10	Store Vildmose	Søren O. Petersen	Aarhus University
	11	Mørke	Søren O. Petersen	Aarhus University
	12	Skjern	Søren O. Petersen	Aarhus University
Germany	13	Ahlenmoor	Heinrich Höper	LBEG
	14	Dümmer	Heinrich Höper	LBEG
	15	Peental	Jürgen Augustin	ZALF
	16	Rhin-Havelluch	Jürgen Augustin	ZALF
	17	Donauried	Matthias Drösler	TUM
	18	Freisinger Moos	Matthias Drösler	TUM
	19	Benediktbeuern	Matthias Drösler	TUM
	20	Mooseurach	Matthias Drösler	TUM
	21	Kendlmühlfilze	Matthias Drösler	TUM
Poland	22	Rzecin	Bogdan Choijnicki	ACAUP
Sweden	23	Storflaket	Torben Christensen	GBC
	24	Stordalen	Torben Christensen	GBC
	25	Skogaryd	Leif Klemedtsson	Uni-Göteborg
	26	Falköping	Leif Klemedtsson	Uni-Göteborg
	27	Fäjemyr	Magnus Lund	BGC
Finland	28	Kaamanen	Tuomas Laurila, Eeva-Stiina Tuittila	FMI
	29	Lompolojänkkä	Tuomas Laurila	FMI
	30	Siikajoki	Eeva-Stiina Tuittila	Metla
	31	Alkkia	Tuomas Laurila	FMI
	32	Aitoneva	Harri Vasander, Mika Aurela	UHEL, FMI
	33	Siikaneva	Timo Vesala; Eeva-Stiina Tuittila	UHEL
	34	Vesijako	Kari Minkkinen	UHEL
	35	Jokioinen	Tuomas Laurila	FMI
	36	Lettosuo	Tuomas Laurila	FMI
	37	Kalevansuo	Tuomas Laurila; Kari Minkkinen	FMI
Greenland	38	Zackenberg	Mikkel P. Tamstorf	University of Aarhus
	39	Kobbefjorden	Mikkel P. Tamstorf	University of Aarhus

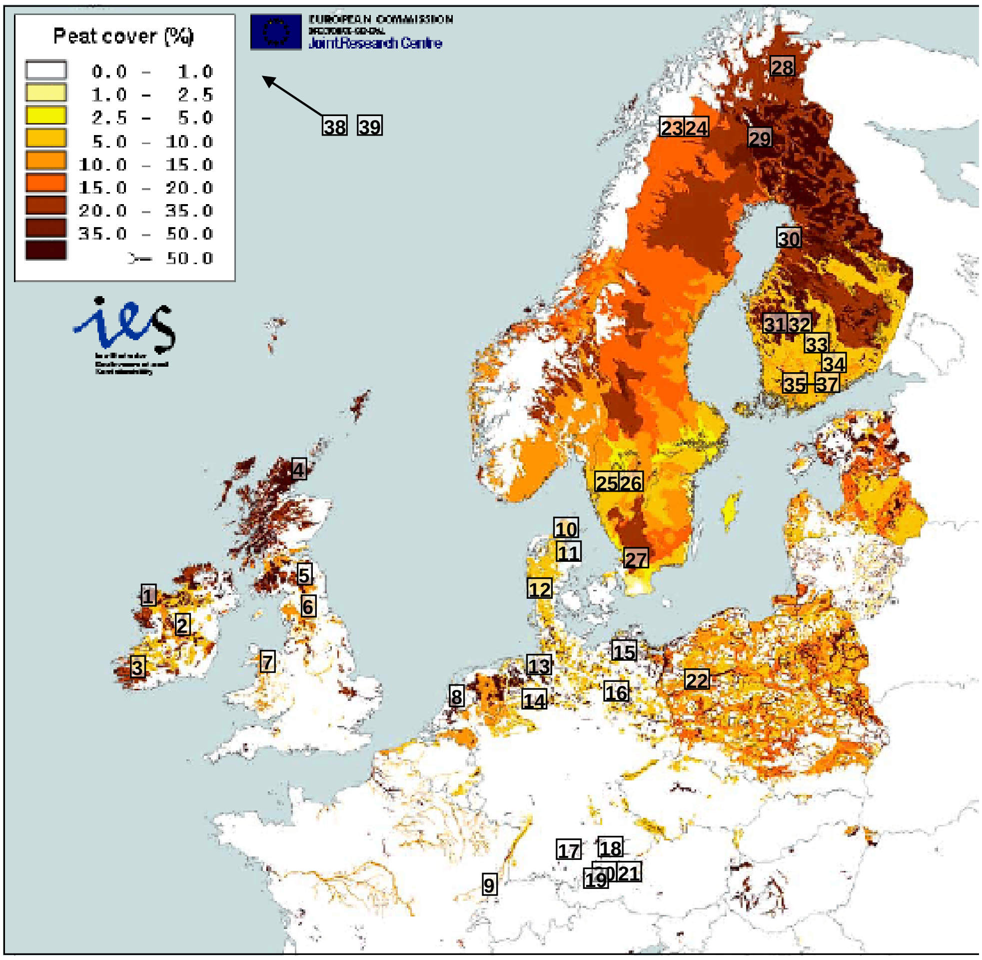

Figure 1: Contributing peatland sites.

Additional measurements will be funded by the *GHG-Europe* project to complement existing datasets. Peatland CO_2 and CH_4 models will be further developed based on these observational data and an N_2O module will be added.

The impact of **forest management, N deposition and climate on forests** will be studied in **Task 2.2**. N deposition was found to enhance C sequestration in forest (Magnani et al., 2007) and long-term C stabilisation of soil organic carbon (Berg and Matzner, 1997; Schimel and Weintraub, 2003). However, the N effect seems to be non-linear and may saturate at relatively low N doses. It is also unclear how long the additional N will affect C turnover in forest soils, whether the seasonality of N deposition matters and how fast the N will be lost again. Therefore, past N fertilization experiments with ^{15}N labelled doses will be resampled. The forest databases compiled in the EU projects CarboEurope-IP and NitroEurope-IP will be expanded with additional driver information and re-analyzed.

The effects of past and present **agricultural management on soil C and CO_2, N_2O and CH_4 fluxes** in croplands, low-input and high-input grasslands will be studied in **Task 2.3**. **CO_2, N_2O and CH_4** fluxes are directly influenced by tillage practice (conservation tillage, conventional tillage) and the fertilization (organic and mineral). While in natural ecosystems the carbon and nitrogen balance is dominated by gaseous exchange with the atmosphere, C and N budgets in managed agricultural systems need to include biomass export by harvest and fertiliser application. Site properties are often critical for the magnitude of **CO_2, N_2O and CH_4 fluxes** response to C and N input – so there is a particular challenge to disentangle the natural (including ecosystem properties) and anthropogenic drivers. For the purpose of separating various drivers we will make use of long term experiments and observational studies on **CO_2, N_2O and CH_4** fluxes and C pools including different treatments of land management and fertilisation. Moreover, at selected sites soils will be resampled and SOC fractions determined in order to initialize model compartments from measured values.

Land use change is seen as one of the primary determinants of ecosystem vulnerability and a major human impact on European GHG budgets (Rounsevell et al. 2006, Janssens et al. 2003; Smith et al., 2005) and will be the focus of **Task 2.4.** In the future, land use change rates are expected to remain at a high level, or to increase due to land use conversions into bioenergy production systems. However, only few field-based studies are available to assess soil C changes in relation to the various land use changes within regions with different climate and land use history. Recent attempts to review and synthesize effects of land use change on soil C and GHG fluxes were mainly based on global datasets and uncertainties are large (Post and Kwon, 2000; Guo and Gifford, 2002; Jandl et al., 2007). There is little knowledge on the combined influence of land use change and interacting factors such as land use history, soil type and climate, and such interacting factors may currently contribute to the large variability observed in effects of land use change. Moreover, many studies rely on soil data that were not designated as a reference for changes in SOC. Typical shortcomings are shallow sampling depth that fail to account for changes occurring also in the deeper soil or missing measurements of bulk densities, coarse soil fractions and stone content. A pan-European resampling of existing experiments and monitoring sites with chronosequences and paired plots of different land use will reveal the first comprehensive assessment of the effect of land use changes on soil C stocks at the European scale. Land use conversions into bioenergy crops will be included to account for the predicted increase in bioenergy production.

Mediterranean shrublands and South East European forest were identified as under-sampled areas with a high potential to increase our knowledge on how GHG emissions are controlled in different ecosystems. New **CO_2, N_2O and CH_4** measurements will be performed in **under-sampled regions dominated by extensification and abandonment of land** in the last decade.

The transition of former Eastern Block countries joining the EU provides an ideal platform to study the impact of past management and management changes on GHG fluxes: Forests in South Eastern Europe cover a wide range of management practices including exceptionally large unmanaged parts, coppice systems and more intensive forest management practices. In these ecosystems, little research on **CO_2, N_2O and CH_4** fluxes has been performed, but in Romania a unique forest inventory with more than 50,000 sample plots with C stocks in soil and biomass has been started in 2007. These data will be available to explore the impact of forest management, including afforestation on C stocks and to select sites with a strong management gradient to set up the first Romanian GHG flux stations (**Task 2.5**). These studies will have strong synergies with Task 2.2 on the effects of N deposition and climate variability in forest ecosystems. For the first time a **full CO_2, N_2O and CH_4 budget will be provided for the very diverse Eastern European forests** ranging from intensively managed coppice systems to pristine ecosystems. The unique joint forest inventory with tree ring data and complete soil profile data will be used for a detailed differentiation between the effects of **past and present forest management on C stocks (Task 2.5)**.

Shrublands cover large parts of the Mediterranean with considerable enlargement in some regions by woody encroachments. Improved data and process understanding of **woody encroachment** (called “revegetation” under the UNFCCC) will be gathered as a precondition for a better representation of shrublands in process-based models for European GHG balances. Due to low nitrogen and reduced water availability in shrublands N_2O and CH_4 fluxes may be assumed to be negligible compared to CO_2 fluxes. Thus, in order to understand the role of shrublands for C emissions or sequestration existing shrubland studies and additional measurements will be explored (**Task 2.6**).

WP3 Impact of land management on the regional scale GHG balance of selected, data rich regions in Europe

WP3 aims to provide data-rich case studies and observational evidence of regionally coherent changes in drivers and of ecosystem response. This includes CO_2, N_2O and CH_4 observations and detailed historical driver data in selected, data rich regions of Europe representative of typical

regional trends in land use and management. Based on the variety of available data sets for various drivers and CO_2, N_2O and CH_4 fluxes, WP3 will develop methods for systematic uncertainty estimates in scale representation over heterogenous landscapes and attempt a top-down verification of the CO_2 and CH4 budget of two regions at high resolution (Netherlands, France).

The region is the scale at which land use decisions are ultimately made. **The chosen regions represent a wide range of different soils, land use history, climatic conditions and socio-economic background, as well as differences in trends in land use response to changing policies and markets.** Several trends are particularly important: the results of changes in the CAP that have led to extensification in marginal areas, land abandonment and afforestation, land abandonment after the political changes in 1990 in Eastern Europe and a partial recent re-intensification, the recent forestry intensification (C-forestry) and rise in demand for bioenergy and wood products, changing land use practices, the increasing N-deposition and climate change. Unravelling the impact of these trends on the regional scale **CO_2, N_2O and CH_4** balance is the prime objective of WP3.

In contrast to WP2, WP3 will make the next step from site level responses to changing drivers towards **description of spatial patterns of GHG fluxes at landscape to national level driven by the mosaic of regional environmental and social conditions in a consistent, coherent manner**. The regional studies provide data to the synthesis activities in WP2, consistency constraints to the driver fields developed in WP1 and are used as high-quality calibration and validation for the models in WP4 and WP5 for attribution and vulnerability assessment in data rich regions.

A region is defined in a diagnostic sense as an area comprising a mosaic of land cover and associated C and GHG fluxes for a range of environmental conditions and land uses subjected to comparable climatic conditions. We also include an Alpine region, where altitudinal gradients allow an assessment of **climate-driven responses**. The GHG balance of regions depends critically on the spatio-temporal integral of land use history, management and climate (Caspersen et al. 2000). These processes have generally been looked upon at relatively coarse resolution (>50km). European landscapes typically present a heterogeneous mixture of forests, croplands, grasslands and wetlands with different land use history and management practices at much smaller scales (Dolman et al., 2008). WP3 is concerned with the crucial scale in between the ecosystem analysis (WP2) and the European wide modelling (WP4, WP5, WP6), where, over a gradient of land use, management and climate, we will study the impact of land management at the scale where day-by-day decisions are made: land use and management practices are defined and executed at farm level, landscape level and national level. **Lateral flows of C and N**, in particular input by fertilizer and output by harvest can only be traced in a spatially explicit way at the regional level where detailed farm and forest management information is available. **In cooperation with the modelling in WP4 and WP5, WP3 will calculate CO_2, N_2O and CH_4 budgets at farm gate level, regional and national level.**

The data density that allows such a detailed study is not the same all over Europe, hence we selected **6 regions with the required data density in driver data** (Table 1.2): high resolution (1 km or higher) soil and forest biomass inventory, maps of land use history, and management history and climate and weather data for the present and several decades backwards. The **required data density in C and CO_2, N_2O and CH_4 flux data** was: multi-year site level observations of CO_2 and energy exchange by eddy covariance in the most important land use systems (operated during the project), additional **N_2O and CH_4** flux data by chamber measuremets to allow the calculation of the full GHG budget by land use and ecosystem type, and studies along regional gradients of land management intensity, soil properties, climate. All regions also offer data from **factorial experiments and partly also ecosystem manipulations** (land use change, N fertilizer type, grazing intensity, elevated CO_2, artificial drought) and will allow us to examine the historical impact and longevity of **past management effects**.

To be able to compare the **CO_2, N_2O and CH_4** balance between the regions and with the European analysis in WP4 we will execute a **detailed error and uncertainty analysis that in two regions includes a top down constraint by atmospheric models and data** (e.g Lavaux et al. 2007). Scaling local observations to regions or continents e.g. with the help of remote sensing and models, requires a careful analysis of their representativeness for these larger areas. Particularly important is the spatial scale of coherence in the error of the model used for upscaling: depending on this scale, errors can either cancel out when integrating over large scales, or they contribute to large-scale biases. We will develop a methodology to quantify this error in upscaling and downscaling.

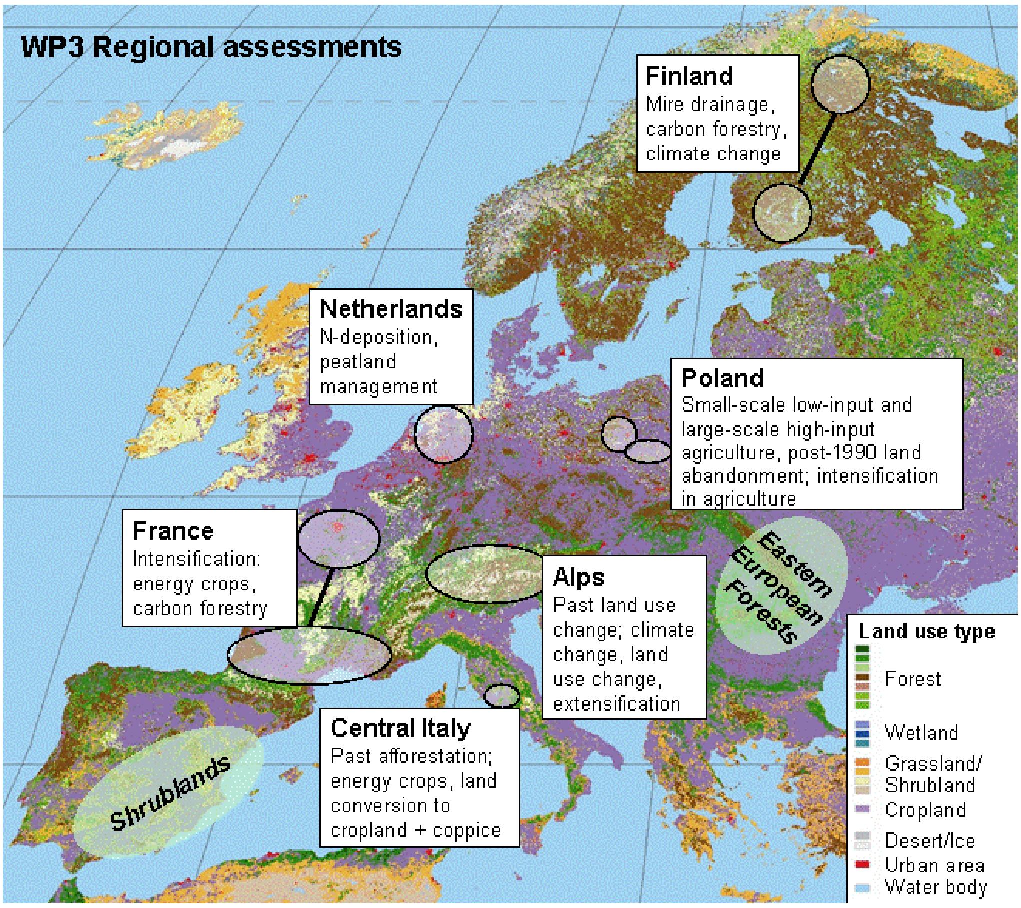

Fig 2: Six selected data rich regions with different vulnerability to natural and anthropogenic drivers. Undersampled ecosystems (shrublands, Eastern European forests) addressed in WP2 are also shown.

By applying the same models as used at the European level in WP4 and WP5, we (in collaboration with WP4 and WP5) will assess the vulnerability of the regional **CO_2, N_2O and CH_4** balance to changes in land use and management, and importantly also to identify at which spatial scale the uncertainties reside, so that we can realistically outline a strategy for further uncertainty reduction. At the same time, we will develop a **methodology that will allow more efficient UNFCCC reporting** based on regionally and activity validated upscaling efforts.

The six selected regions (Figure 3) include areas of highly intensive agricultural land use, areas where in particular new land use policies are implemented, areas with changing forestry practice and areas where socio-economic and land use conversion practices are taking place

Table 3: Characteristics and data availability in the six regions; EC: CO_2 and CH_4 measurements by eddy covariance, chamber: **CO_2, N_2O and CH_4** measurements by flux chambers

			Data availability			
Region	**Climate**	**Dominant ecosystem types**	**EC sites**	**Chamber sites**	**N deposition**	**Atmospheric stations**
Alpine	Alpine	Low-input and high-input grasslands, forests	11	4	Extensive	Yes
Nether-lands	Oceanic temperate	Peatlands, low-input and high-input grasslands, forests	5	4	Extensive	Yes
France	Oceanic temperate, Mediterranean	Grasslands, high-input croplands, forests	12	6	Extensive	Yes
Italy	Mediterranean	Low-input croplands, coppice forests, shrublands	7	2	Intensive	No
Poland	Continental temperate	Low-input and high-input croplands, forests, peatlands	3	2	Intensive	No
Finland	Boreal, subarctic	Forests, peatlands	7	3	Intensive	No

WP4: Attribution of annual to decadal variability of carbon and GHG budgets in managed European ecosystems to human and natural driving processes

The overall aim of WP4 is to attribute (with uncertainty) annual and decadal variability of carbon and CO_2, N_2O and CH_4 budgets in managed European ecosystems to anthropogenic and natural driving processes.

In WP4, we will use **sectoral models**, which include a highly developed range of land management descriptions as well as response to climate and other direct / indirect / natural drivers (e.g. atmospheric CO_2 concentration, N-deposition), to quantify the proportion of observed / predicted change in ecosystem C storage and **CO_2, N_2O and CH_4** balance, and the interannual and decadal variability in these measures, to anthropogenic and natural driving processes. For agricultural systems we will use the **Sundial/MAGEC** (**cropland**; Smith et al., 1996), **PaSim** (**grassland**; Vuichard et al. 2007a, b), **DayCent** (**crop and grassland**; Del Grosso et al., 2006), **DNDC** (**crop and grassland**; Li et al., 1994) and **EPIC** (**crop, grassland and forestry**; Izaurralde et al., 2006) models. In addition to the process models described above, **two data driven models**, developed by Freibauer et al. (in prep.), and Soussana et al. (in prep.) will be applied.

Spatially explicit time-series of CH_4 emissions from animal husbandry in Europe, in particular from enteric fermentation, will be downscaled to NUTS-2 level or higher resolution from the National Inventory Reports for the period 1990 to 2010.

For **forestry**, we build on the high resolution inventory based **1x1 km database of European forests**. A hybrid empirical model was build on these data for each km^2 (**EFISCEN –space**); this model combines the data richness of inventories, with the process understanding derived from eddy flux sites. This high resolution modelling allows for the use of data from overlays with GIS material as soil type, weather circumstances, and remote sensing derived photosynthetic activity, etc. The latest biomass expansion factors will be used as well as the Yasso model (Liski et al. 2005) for the soil to complement the full carbon cycle.

We apply **nested simulation modelling**, to assess the importance of physiological processes, versus anthropogenic drivers; the latter as determined by regionally specific forest management. This mean we will have an empirical 1x1 km forest-soil model (EFISCEN-space), complemented with a more detailed plant physiological model (Forgem) that is partly fed by remote sensing derived photosynthetic activity. In this way, the regional circumstances for optimal carbon management can be taken into account considering as well mitigation effects in the harvested wood product pool under different policy scenarios (Eggers et al. 2008, Nabuurs et al. 2008). The forestry work is closely coordinated with the work on forest age classes in WP1, as well as forest related assessments in WP2.

In the **first phase of the work** (**Task 4.1**), each model will be evaluated against existing datasets from previous projects, and additional data from WP2 and WP3. Each model will be evaluated against existing datasets from previous projects (e.g. *CarboEurope-IP*, *NitroEurope-IP*, *CC-TAME*, *CARBO-Extreme*), and additional data, particularly from WP2, and some from WP3 (but not those used for regional attribution in WP 4.2). The **models will be tested at site level** to ensure that they capture the annual and decadal scale variability found in the datasets under different natural climatic and non-climatic drivers, and under different management. A suite of state-of-the-art statistical methods, developed over the past decade (e.g. Smith et al., 1997; Morales et al., 2005; Smith & Smith, 2007) will be used to assess the performance of each model (error, coincidence, association, bias) for each dataset. The ability of the models to capture variation in C pools and **CO_2, N_2O and CH_4** fluxes found at the sites tested will be assessed, as will the attribution of the observed changes to the various drivers present in each of the different datasets. For models able to simulate the same land use, outputs and attribution will be compared. Those models that are shown to successfully capture the variability will then be used to simulate in detail the data-rich regions from WP3.

All models applied are point models that are applied to any area that can be assumed to be homogeneous. When applied at a site, they can easily be applied in this way. When applied in the data rich regions, detailed spatial data (in a GIS) will be used. The region is divided into homogeneous response units (HRU; same land cover, management, soil type etc.). A similar approach has been used in CarboEurope-IP and NitroEurope-IP, and is a tried-and-tested method. The models run for each HRU and outputs are given for each HRU within the region. The outputs can be mapped spatially and aggregated to the region as appropriate. At pan-European level, the procedure is similar, but the spatial resolution of the pan-European HRUs is lower. Each model is run using spatial data on, e.g. soils, land cover, land management, climate etc., for each pan-European HRU. The HRUs at pan-European scale have a lower spatial resolution than those used at the regional level, but the principle is the same. Again, this approach has been used in countless previous European projects including ATEAM; CarboEurope-IP, NitroEurope-IP, CC-TAME, Carbo-Extreme and many others. It is a tried and tested method, in common use among the modelling teams. At each scale of application, the uncertainty associated with the data used to drive the models, will be thoroughly assessed as described in the work plan (see especially WP4, 5 and 7).

In **Task 4.2**, the detailed fields of driving variables from WP3 will be used with the models to **simulate measured changes in C pools and CO_2, N_2O and CH_4 fluxes in the data-rich regions from WP3**. The models will be run in a factorial manner (first including variability in all drivers, then holding one driver at a time constant) to quantify the contribution of the different drivers to the observed C stocks, **CO_2, N_2O and CH_4** fluxes and spatial and temporal variability in these measures in the WP3 regions. A formal detection and attribution technique, known as optimal fingerprinting, developed to isolate the causes of observed change will be used. Using this method, the models are run with all factors included, and allowed to vary within set ranges. The models are then run again, fixing one potential driver at a time. By comparing the model outputs to the observations, the distinct spatio-temporal patterns of the response serve as ‘fingerprints’ that allow the observed change to be separated into contributions from each factor (Tett et al., 2002; Gedney et al., 2006). We will further develop these formal detection and attribution techniques (originally developed for climate attribution) and use them to attribute annual to decadal variability of carbon pools and **CO_2, N_2O and CH_4** budgets in managed European ecosystems to human and natural driving processes. The optimal fingerprint from each model will be compared to provide an ensemble approach to attribution, with the proportional contribution from each driver in each model compared to give a range of contributions, as simulated by a number of conceptual formulations of the ecosystems encapsulated within the different models. This will partly inform the sensitivity / uncertainty analysis performed in Task 4.3, though that more formal analysis will allow a more probabilistic assessment to supplement the model ensemble range delivered here in Task 4.2.

A **formal global sensitivity and uncertainty analysis will be undertaken for all WP4 models** (**Task 4.3**), using data in Tasks 4.1 and 4.2, using Bayesian and Monte Carlo techniques developed primarily in *CarboEurope-IP* and *NitroEurope-IP* and described in detail elsewhere (van Oijen et al. 2005, Gottschalk et al., 2007; Larocque et al., 2008). The model parameters found to be most sensitive (i.e. having the largest influence) on ecosystem C and **CO_2, N_2O and CH_4** fluxes will be determined via global sensitivity analysis (when all varied model parameters are allowed to vary within their initial probability density functions, and each is then held constant in turn, one by one; Hamby, 1994; Saltelli et al. 2000) using the Sensitivity Index (Smith & Smith, 2007). The parameters may not be the same for each model and for each dataset. The sensitive parameters will then be used in the global uncertainty analysis. In a similar manner, the five to ten sensitive model parameters will be allowed to vary within their initial probability density functions, and each will then held constant in turn, one by one. Instead of assessing the impact on the output parameters (e.g. C or GHG flux), the impact of input / parameter variability on output variability (uncertainty) will be assessed using the Importance Index and Relative Deviation Ratio (see Smith & Smith, 2007). This will allow uncertainty in the model outputs to be quantified, which in turn will allow the model outputs on attribution to the different natural and human drivers to be interpreted. Task 4.3 will, therefore, allow **not only model uncertainty to be quantified, but also uncertainty in the attribution of observed differences in plot level, regional and pan-European level C and GHG fluxes to be quantified for each model in the sectoral model ensemble**.

In **Task 4.4** the sectoral models will be run at pan-European scale, under recent, current and future conditions using driving datasets collated in other projects (*CARBO-Extreme*, *CC-TAME*) and in WP2, **to attribute annual to decadal variability of carbon and GHG budgets in managed European ecosystems to anthropogenic and natural driving processes**. The uncertainty analysis of Task 4.3 will be used to quantify the uncertainty associated with attribution of changes and variability in C and GHG fluxes to anthropogenic versus natural drivers from the sectoral ecosystem models. The results will provide pan-European data fields for use in the assessment of future vulnerability of C stocks and GHG emissions in European managed land in WP6. The outputs from Task 4.4 will be compared pan European estimates made using data oriented / generic model / top down techniques in WP5. The integration of bottom up sectoral approaches, with top-down approaches has proved very powerful in previous projects in applying a dual constraint approach to pan-European estimates of C and GHG fluxes and their variability (e.g. Janssens et al., 2003; Schulze et al., 2008).

WP5: Quantification of the annual to decadal magnitude and variability of the C and GHG budget of European terrestrial ecosystems for EU 27

The goal of WP5 is to quantify the full European carbon balance and its annual-to-decadal variability in an integrated approach. In contrast to the sectoral and full GHG view of WP4, WP5 uses the strength of generic models to quantify carbon compartment fluxes in ecosystems, to include all ecosystem types (with less detailed management) and to include land use changes. Process-oriented and data-oriented ecosystem models, and atmospheric concentration measurements and inversion models will be integrated. We selected state-of-the-art process-based models that include parameterization of ecosystem management, in order to analyze the covariance between management and climate at various scales, and its impact on the carbon balance. Two **state-of-the-art process-oriented models LPJml** and **ORCHIDEE** will be run over the regions with data from WP3 and for the EU27+ for the period 1900 to 2008 with a focus on the 1990-2008 period. These simulations will be then updated each year of the project and extended up to the year 2010. Five forcing fields will be considered: climate**, rising atmospheric CO_2, nitrogen deposition, land use change and land management**. These drivers will be based on data acquired in WP1. Three main types of managed ecosystems and transitions between them will be considered: croplands, grasslands and forest. Different age classes will be considered for forest and land use change to correctly simulate the biomass and soil carbon dynamics.

The same driver data will be used to run the **data driven model**, developed by Freibauer et al. (in prep.), which is parametrized with the response functions from WP2 and also used in WP4. Two additional data driven approaches will be applied to produce alternative spatially explicit response functions at regional and EU27+ level by artificial neural networks and a hierarchical regression model tree. These data oriented approaches ensure across scale consistency and allows a larger number of scenario runs due to its high computation speed.

The results of the process-oriented and data driven modelling will be **regional high resolution maps** and **European maps of main carbon stocks and fluxes** (e.g NEE, NPP, GPP, living biomass, soil carbon) on a 0.25x0.25° grid for EU27+**,** and a **sensitivity analysis to each driver**.

Models results will be evaluated against ecosystem-scale data base on data acquired in WP2 and WP3 (e.g ecosystem fluxes, inventory, agricultural statistics) in particular to access models uncertainties. They will be also compared to atmospheric large scale inversion and results from data oriented models. Management-climate covariance will be calculated by factorial simulations, in which one driver is fixed and the others are variable. Drivers of land-use change, forest and crop management intensity and practice, and climate will be prepared in WP1.

In a first evaluation step and in analogy to Task 4.1, the wealth of existing *Carboeurope-IP* data, complemented with new data collected by WP2 and WP3 will be used **to evaluate the models at site level**. The focus of this model evaluation activity will be given to soil C change chronosequences after land-use transitions (in cooperation with Task 2.4), and to the long time series of eddy-covariance CO_2, water and heat flux measurements. Process-oriented model results (**Task 5.1**) and data oriented model results (**Task 5.2**) will be compared with each other, and with data, not only for their predicted CO_2 fluxes (regional distribution, interannual variability) but also for their *sensitivity* to each driver.

In a second evaluation step (**Task 5.3**), atmospheric concentration data from 15 atmospheric concentration measurement stations will be assimilated by inversion models in order to produce time varying **maps of CO_2 fluxes at intermediate resolution (100 to 500 km; weekly) over the period 1996-2007**. Three inverse modeling groups, funded by national sources, will participate to this exercise (see Letters of Intent, Appendix 3). Inversion results will be compared between inversions, and with ecosystem model fluxes, for the seasonal and interannual variability. The carbon flux anomalies of heatwaves of summer 2003, summer 2005 and autumn 2006 will be investigated. The decadal mean CO_2 budget of the main bioclimatic regions of Europe, and its uncertainties, will be quantified by inversions. We will identify 'hot spot' regions where mean flux, or variability in fluxes in response to changing drivers is particularly important.

The project will benefit from new advances of inversion methods developed during *CarboEurope-IP* to i) meet the scale at which ground measurements take place, ii) best combine information from atmospheric measurements and prior information on land fluxes (i.e., using ecosystem models) and iii) estimate uncertainties associated to the spatial and temporal distribution of the fluxes (i.e. error of the mean fluxes and their interannual variations). Because of budget limitations, priority is given to sustain a high-quality atmospheric CO_2, CH_4 network without which inversions could not deliver results. Three leading inversion modeling groups, CEA-LSCE (P. Peylin), MPI-BGC (C. Roedenbeck), and Wageningen University (W. Peters) are engaged to contribute to this task by running their inversion system, but with external sources of funding.

The synthesis of the continental scale carbon budget (Task 5.4) will proceed into three consecutive cycles, in a roughly sequential order.

<u>Cycle-1, Months 0 to 18.</u> In parallel with new data collection programs, modellers will pursue and extend analysis of *Carboeurope-IP* data. The past *Carboeurope-IP* synthesis (Ciais et al., 2009 a&b; Luysaart et al., 2009; Schulze et al., 2008) will be extended by **analyzing the processes controlling the component fluxes: GPP, NPP, RH, NEP, NBP for each region and each ecosystem**. We will define the model-data comparison protocols linking WP2 and WP3 to the integration in WP5. The first comparison between atmospheric inversion and ecosystem models for regional fluxes will be performed.

<u>Cycle-2, Months 12 to 30.</u> New model runs will be integrated over the **period 1900-2008, with separation of drivers**: climate, land use change, and management intensity changes within each land

use type (fertilizers and tillage for crops, fertilizers for grasslands, age-class structure for forests). A *mid-term synthesis* of the European C balance will be provided by Month 30.

Cycle-3, Month 30 to 42. Model runs of Cycle-2 will be extended to produce a regular yearly update of the carbon balance of Europe. Full GHG balance will be estimated by combining sectoral models output maps from WP4 for N_2O and CH_4 fluxes, with CO_2 fluxes from the WP5 models. Detailed model-evaluation against atmospheric inversion results will be done. A *final synthesis* will be provided by Month 42.

WP6: Future vulnerability of sources and sinks and risk of positive feedback with climate change and European politics – post-2012 scenarios

WP6 aims to assess the risk of positive feedback in the climate-carbon system by scenarios with typical and extreme variations in drivers, projections with realistic drivers and by modelling feedbacks with global bioenergy and timber markets and climate policies in the post-2012 climate regime. The overall objective of WP6 is to draw guidelines and recommendations on land-use practices to be promoted by EU policies.

Climate change and climate policies will affect GHG budgets in the land use sector. The choices among mitigation and vulnerability management strategies will depend on the associated economic costs and benefits. WP6 will use the outputs from biophysical model developed and applied in WP4 and WP5 to an existing economic modelling cluster built to assess post Kyoto policy strategies. In this way **economic models will assimilate** the wealth of **biophysical information** generated by *GHG-Europe*. This modelling cluster was developed by IIASA for policy analysis in close coordination with the direct users of the results in European Commission services. The modelling cluster will be used within *GHG-Europe* to assess the economic impacts of climate change and of climate policies on the agricultural and forestry sectors on national and European levels. The economic models will provide **scenarios of land use and management** for Europe **constrained by changes in global demand for timber and bioenergy and future climate policies**, which will also be reflected in the scenario driver fields in WP1.

Two distinct strands of analysis will be carried out. First we will carry out a **broader analysis of integrated multi-sectoral policy designs** with the aim to **maximize European value added for post-Kyoto strategies** given existing and emerging sectoral policies (agriculture, forestry, bioenergy and environment) by reaping ancillary **co-benefits from European policy integration** in a global context (policy leakage). This will be accompanied by a **detailed technical analysis of how land use practices are affected by policies** to support European climate policies given the constraints and context of the ongoing negotiations. Second, we will carry out **long-term scenarios** focusing on **vulnerability assessment and the potential contributions and risk of the European LULUCF sector for long-term aspirational climate targets**.

Near and medium term scenarios (until ~2030) to study the impact of post-Kyoto policies (mitigation scenarios): Changes in land use and management and in associated GHG budgets induced by policies, in particular by the **Common Agricultural Policy, Rural development Strategy, EU Forestry Strategy and Forest Action Plan, and in general EU policies on climate change** will be assessed. The results from the integrated model cluster will be used to provide quantitative assessments in terms of **cost-efficiency and environmental effectiveness** of individual land-use practices, competitive LULUCF mitigation potentials (taking into account ancillary benefits, trade-offs and welfare impacts), and policy implications in terms of instrument design and the international negotiation process. The proposed structure of the model cluster allows to provide an evaluation of policy options at a great level of detail for EU27 in a post-Kyoto regime, as well as to offer perspectives on global longer-term policy strategies in accordance with the principles and objectives of the UNFCCC in a wider European land-use policy context. The Post-Kyoto assessment will **quantitatively evaluate the potential impacts of existing EU legislation** based on the latest perspectives on economic development, energy and agricultural policies and agreements on GHG emissions reductions, as well as explore the **scope for further cost-effective measures** to reduce

GHG emissions from the LULUCF sector. The analyses will be carried out in close cooperation with the European Commission services to maximize the policy relevance of the assessment.

Longer term scenarios until 2100 to study the feedback between land use, policies, and climate (mitigation and adaptation scenarios): These scenarios focus on vulnerability management. Thus, mitigation and adaptation to climate change will be combined. These scenarios will be conducted **in accordance to the scenarios developed for the IPCC AR5**. Assessment of **the efficiency of long-term land use adaptation and mitigation** processes will be carried out by quantifying the **net accrual of GHGs to the atmosphere** in the context of wider sustainability impacts for individual management practices. **Vulnerability assessment** will be performed in a **bottom up fashion where adaptive measures are endogenously selected by the economic model and include biophysical adaptation on the site as well as adaptation through trade**. On site adaptation measures may range from changing crop rotations, planting times, irrigation scedules, pesticide application and fertilization regimes. These direct adaptation needs due to driver changes will be quantified in a spatially explicit way. On the other hand indirect market effects, such as relocation of production from drought prone areas, will become visible only through changes in interregional trade flows of the major agricultural crops, forest products as well as biomass products. The remaining impacts will be reported in physical terms (yield and GHG losses) as well as in economic terms.

WP7 Scientific consistency, uncertainty methods and data base

The main objective of this WP is to facilitate and track the integration between the observations and modeling activities in the project via a central database with quality control and the provision of uncertainty analysis tools.

Model needs (WP4, WP5, WP6) and observations (WP1, WP2, WP3) will be evaluated to find the best link and collaboration inside the project. Data collected will be available in a project database including other data sources coming from former projects, in a standardized and harmonized format, quality checked and together with uncertainty estimation and complete metadata. These activities will be based on the experiences gained from other projects like *CarboEurope-IP* and *IMECC* where however only eddy covariance and atmospheric measurements have been standardized and quality controlled. In this project the data sources are much more heterogeneous including point measurements, spatial data (WP1, WP2, WP3) and process analysis results (WP2). New methods to quality control, harmonize and standardize the data entries to the database will be developed. It will also be critical to ensure coherence with other databases of field measurements, e.g. in *NitroEurope-IP* and to ensure the coherence with the eddy covariance data standardized by other projects, e.g. *CarboEurope-IP*, *IMECC* and *FLUXNET*.

In addition, methods for the uncertainty definition and assessment will be developed and applied to both data and model outputs. Finally standardized tools for the propagation of uncertainties will be provided and made available for use in the project with data oriented models, simplified process models and in data analysis.

WP7 is hence central in ensuring consistency in data and in uncertainty analysis across all Work Packages. WP7 plays a crucial role in ensuring continuity in data quality and accessibility from past EU projects and, after termination of *GHG-Europe*, of the project data and results to the wider scientific community.

WP8 Coordination and dissemination

This WP is dedicated to the organization, management and administration of the project and to disseminate the project results to science, policy and society.

VTI will **coordinate** the project with a small effective Project Management Team (Fig. 2.1) with proven leadership (**Task 8.1**). The Coordinator Annette Freibauer has already coordinated several EU projects since the 4^{th} EU Framework Programme (FP4), including the CarboEurope cluster of projects in FP5 and the *CarboEurope-IP* Integrated Project in FP6. She will be supported in the daily project management by a Project Manager and in finances and organisatorial matters by an Administrator. For details see Section 2.1.

The project results are **disseminated** to science, policy and society via a **wide range of well-established, stakeholder-oriented methods and pathways** (**Task 8.2**) in strong coordination with policy-relevant activities in WP6. For details see Section 2.2.

Intellectual Property Rights are ensured via the *GHG-Europe* **data policy** which will be part of the Consortium Agreement. For details see Section 2.2.