The significance of remote sensing in the Good Practice Guidance for Land Use, Land-Use Change and Forestry as specified by the Kyoto Protocol

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Abstract

The significance of remote sensing in the Good Practice Guidance for Land Use, Land-Use Change and Forestry as specified by the Kyoto Protocol

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The Kyoto Protocol to the United Nations Framework Convention on Climate Change (Kyoto Protocol) is an international agreement to reduce greenhouse gas emissions and mitigate global climate change. Within the period of 2008 to 2012, the Protocol requires a reduction of emissions of 5% to the level of the year 1990. *The Good Practice Guidance for Land Use, Land-Use Change and Forestry (GPG-LULUCF)*, published by the Intergovernmental Panel on Climate Change (IPCC), is laid out to assist countries in preparing their greenhouse gas inventories. It provides definitions and methodological advice especially for the sectors land use, land-use change and forestry. This thesis provides a review of the *GPG-LULUCF* and presents how remote sensing is taken into consideration. Due to the importance of forestry in Austria (forest land covers nearly 50% of the total area), special emphasis is given to the correlation between remote sensing and forestry. As one procedure with great potential, the *GPG-LULUCF* introduces the field of remote sensing and gives examples of how remote sensing can contribute to reach the targets required by the Kyoto Protocol. Moreover, recent international research trends regarding remote sensing and the Kyoto Protocol are discussed. The author comes to the conclusion that it is still left up to the remote sensing community to demonstrate the usefulness of remote sensing for verifying changes in living biomass and to improve our understanding of the terrestrial carbon cycle.

Keywords: remote sensing, Kyoto Protocol, land use, forestry, national forest inventory.

Zusammenfassung

Die Bedeutung der Fernerkundung im „Good Practice Guidance for Land Use, Land-Use Change and Forestry“, vorgegeben durch das Kyoto-Protokoll

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Das Protokoll von Kyoto zum Rahmenübereinkommen der Vereinten Nationen über Klimaänderungen (Kyoto-Protokoll) stellt ein internationales Abkommen zur Reduktion von Treibhausgasemissionen und zur Bekämpfung des Klimawandels dar. Das Protokoll sieht eine Reduktion der Emissionen in den Jahren 2008-2012 von rund 5% auf das Niveau des Jahres 1990 vor. Der Leitfaden *Good Practice Guidance for Land Use, Land-Use Change and Forestry (GPG-LULUCF),* veröffentlicht von der Zwischenstaatlichen Sachverständigen-gruppe über Klimaänderungen (IPCC), soll den einzelnen Vertragsstaaten bei der Erstellung ihrer Treibhausgasinventuren helfen, indem er Definitionen und Ratschläge speziell für die Bereiche Landnutzung, Landnutzungsänderung und Forstwirtschaft erteilt. Die vorliegende Diplomarbeit stellt diesen Leitfaden vor und untersucht, welcher Stellenwert der Fernerkundung beigemessen wird. Bedingt durch den hohen Waldanteil in Österreich (knapp 50% der Staatsfläche sind bewaldet) wird speziell auf den Zusammenhang zwischen Fernerkundung und Forstwirtschaft eingegangen. Der *GPG-LULUCF* erachtet Fernerkundung als viel versprechende Technik und zeigt auf, wie diese genutzt werden kann, um Ziele des Kyoto-Protokolls zu erreichen. Die vorliegende Arbeit gibt darüber hinaus Einblick in das Potential der Fernerkundung und untersucht aktuelle internationale Forschungstrends. Zusammenfassend kann gesagt werden, dass es weiterhin an der internationalen Forschungsgemeinschaft liegt, den Stellenwert der Fernerkundung für die Verifikation von in Biomasseänderungen zu erhöhen, sowie das Verständnis des terrestrischen Kohlenstoffkreislaufs zu verbessern.

Stichwörter: Fernerkundung, Kyoto-Protokoll, Landnutzung, nationale Forstinventur.

Preface

Throughout my studies in Graz, my interest at all times laid in interdisciplinary environmental problems. Keeping in mind that tackling environmental problems needs the strength of diverse expert fields and collaboration, remote sensing could serve as an ideal instrument not only to draw the attention to the violability of nature, but also to identify appropriate solutions. Throughout my internship at the German aerospace centre (DLR) in the summer of 2003, where I worked in the project ‘SIBERIA II’, I learned to know an interesting field of work in remote sensing and a new understanding of scientific co-operation. This was the time when I got to know the group of Wolfgang Wagner in Vienna and decided to intensify collaboration between the universities of Graz and Vienna. May this thesis, following my intention, be a first visible step.

Parts of this work arouse in the framework of the on-going project NEOS-QUICK (Ref. ASAP-CO-002/03), where the capabilities and limitations of earth observation and the Kyoto Protocol reporting are investigated. Based on a multi-sensor approach, the aim of this project is to integrate remotely sensed data and ground observations to gather missing elements of land use and forestry inventories and to estimate aboveground biomass changes. Project partners are the Institute of Photogrammetry and Remote Sensing, as well as a number of Austrian research institutions, service providers, and forestry experts.

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First of all, I would like to thank Wolfgang Sulzer and Wolfgang Wagner for their interest in my work and their constructive supervision and scientific reviewing. Without their help, this thesis would not have been possible.

I am also grateful to Richard Kidd, José Romero, Åke Rosenqvist, Bernhard Schlamadinger, and Peter Weiss for their lively discussions and productive comments. In the end, I would like to express my gratefulness to Sabine Surtmann for the proof-reading and her support.

Contents

List of figures

List of tables

List of acronyms

AIAA	American Institute of Aeronautics and Astronautics
ASAR	Advanced Synthetic Aperture Radar
AVHRR	Advanced Very High Resolution Radiometer
CDM	Clean Development Mechanism
COP	Conference of the Parties
CwRS	Control with Remote Sensing
dbh	Diameter at Breast Height
DUE	Data User Element
EIT	Economies in Transition
Envisat	Satellite
ERS	European Remote Sensing Satellite
ESA	European Space Agency
ET	Emissions Trading
FEA	Austrian Federal Environment Agency
FF	Forest remaining forest land
GEF	Global Environment Facility
Gg	Gigagrams, 10^6 kg
GHG	Greenhouse Gas
GIS	Geographic Information System
GMES	Global Monitoring for Environment and Security
GPG-2000	Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories
GPG-LULUCF	Good Practice Guidance for Land Use, Land-Use Change and Forestry
GWP	Global Warming Potential
ha	Hectare, 10^4 m^2
Hyperion	Instrument onboard satellite EO-1
IPCC	Intergovernmental Panel on Climate Change
IPCC Guidelines	Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories
JI	Joint Implementation

Kyoto Protocol	Kyoto Protocol to the United Nations Framework Convention on Climate Change
LAI	Leaf Area Index
Landsat TM	Landsat Thematic Mapper, Satellite
Lidar	Light Detection and Ranging
LULUCF	Land Use, Land-Use Change and Forestry
MEA	Multilateral Environment Agreements
MOP	Meeting of the Parties
Mt	Megatons, 10^9 kg
NDVI	Normalized Difference Vegetation Index
NFI	National Forest Inventory
NPP	Net Primary Productivity
OECD	Organisation for Economic Co-operation and Development
QuickBird	Satellite
Radar	Radio Detection and Ranging
SAR	Synthetic Aperture Radar
SBI	Subsidiary Body for Implementation
SBSTA	Subsidiary Body for Scientific and Technological Advice
SIBERIA II	Multi-Sensor Concepts for Greenhouse Gas Accounting of Northern Eurasia
SPOT	Système Pour l'Observation de la Terre, Satellite
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WMO	World Meteorological Organization

1 Introduction

Humankind has known about the changes in the earth's climate system for over a century. It was already in the year 1896, that the Swedish chemist Svante Arrhenius described the basic mechanisms of the greenhouse effect. However, it was not until the last decade, that scientists, politicians, the media, and a great number of non-governmental organisations recognised the threat of climate change for the future of our planet. As one of the most outstanding and ambitious environmental programmes ever established, the 'Kyoto Protocol to the United Nations Framework Convention on Climate Change' (Kyoto Protocol) was set up in the year 1997. This agreement is an international treaty on global warming with the aim of reducing the emissions of carbon dioxide and other so called 'greenhouse gases' to a level *'that would prevent dangerous anthropogenic interference with the climate system'* (UN, 1992, p. 9). Major greenhouse gas emitters are industry, traffic, heating and energy production (see JI/CDM, 2004-11-09), which oppose to major sinks such as forests, or the sea. The question whether biological sinks should be included in national greenhouse gas balances led to major controversy during the negotiation process. Forests, for example, can be regarded as a main sink, as they are able to store more carbon in their biomass than they emit through respiration to the atmosphere. The relevance of forest land therefore is obvious.

According to the terms of the Kyoto Protocol, it enters into force when 55 Parties causing 55% of greenhouse gas emissions accept, ratify, or approve it. The entry into force has been blocked over a long period by the Russian federation, mainly for political reasons. On the occasion of its final signing on November 5, 2004 the ratification of the Kyoto Protocol is now complete and will be brought into force 90 days after this date (i.e. in February 2005). This fortunate fact is a milestone in international climate policy after many years of negotiations and drawbacks and paves the way for a better future of our planet (see GUARDIAN, 2004-11-05).

The need for action can be illustrated by the example of the Austrian emission reduction, which is not encouraging. The Austrian Federal Environment Agency (FEA) publishes the

State of the Environment Report, which demonstrates the status of environmental control according to the Environmental Control Act in a 3-year period. Austria has not yet approached its reduction target (FEA, 2004, pp. 397-398). Instead of a reduction of 13% the emissions effectively increased up to 9.6% (until 2001) above the 1990 baseline, as can be seen in Figure 1.

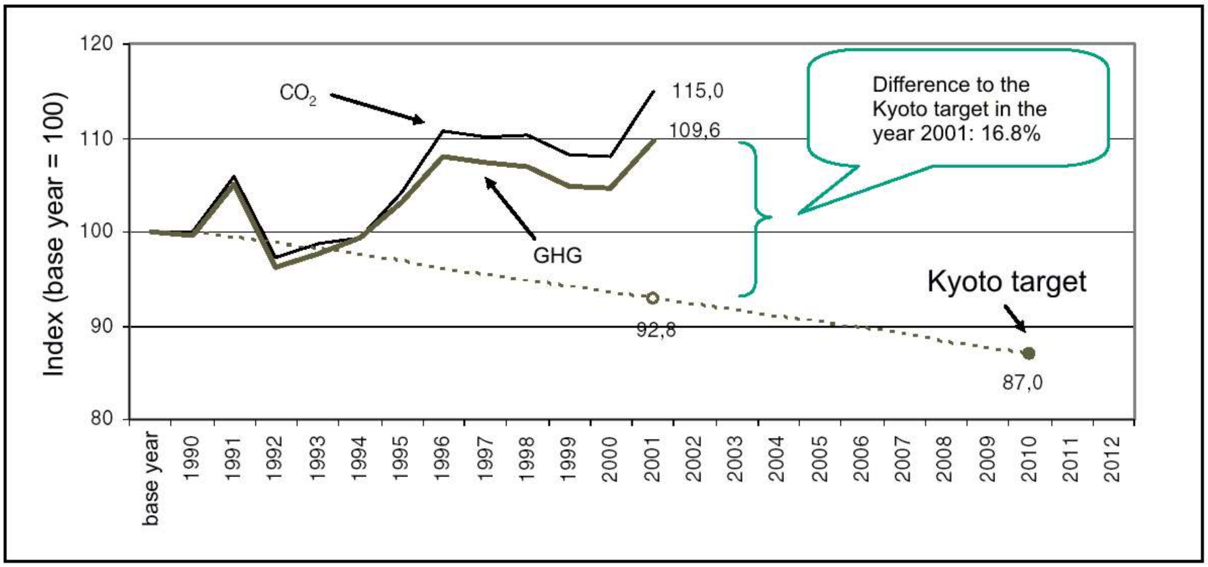


Figure 1: Austria's divergence of the Kyoto target (FEA, 2004, p. 398, modified).

Due to the overall divergence of 16.8%, Austria is on the fourth last position in the European Union! This increase is mainly caused by fossil burning. The highest increasing rates are to be noted in the transport sector, where since 1990 an increase of greenhouse gas emissions of 49% has been observed. For figures that are more recent and an in-depth sectoral analysis, the reader is referred to GUGELE *et al.* (2004).

This development is alarming and far-off Article 3.2 where the Kyoto Protocol describes that *'each Party included in Annex I shall, by 2005, have made demonstrable progress in achieving its commitments under this Protocol'* (UNFCCC, 1998, p. 9). The intention of this 'demonstrable progress' was to act as an 'early warning system' for Parties that run the risk of missing their emission reduction commitments from 2008 to 2012 (ANDERSON, 2003, p. 172). Furthermore, this matter of fact is alarming when bearing in mind that Austria in the 1980's and 1990's served as an example for environmental policy. This case underlines the importance of urgent action, otherwise this could lead to a journey into the unknown.

In order to help Parties fulfil their commitments, the ‘United Nations Framework Convention on Climate Change’ (UNFCCC) has published several reports and guidelines. One of these is the *Good Practice Guidance for Land Use, Land-Use Change and Forestry (GPG-LULUCF),* which is a set of instructions on how to establish national greenhouse gas inventories. One of the shortly introduced topics in this Guidance is the field of remote sensing.
According to REES (1990, p. 1) *‘remote sensing is a subject which is notoriously difficult to define in a satisfactory manner’*. LILLESAND *et al.* (2004, p. 1), though, define the term remote sensing as ‘*the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation’*. In the present thesis, the term remote sensing is understood, broadly speaking, as the use of a sensor onboard of a spacecraft or aircraft to record data about the earth’s surface.

The hypothesis of this work is that remote sensing is a valuable tool for the ‘land use, land-use change and forestry’ sector (LULUCF) in many ways, namely the estimation of changes in biomass, the assessment of land-use changes, as well as the quantification of uncertainties and several verification matters.

To examine this hypothesis, at first an explanation of the basic terms and definitions as well as the provisions of the Kyoto Protocol is given in Chapter 2.
The following Chapter 3 examines state-of-the-art technologies in remote sensing as well as the use of remote sensing in forest inventories.
The main part of the present thesis, which is Chapter 4, is an introduction and discussion of the Good Practice Guidance for Land Use, Land-Use Change and Forestry. This is done by an in-depth review of the document with special emphasis on the importance of remote sensing.
The findings of the previous chapters as well as the impact of remote sensing, together with difficulties and future trends are finally discussed in Chapter 5.
The results are finally summarised in Chapter 6, which also gives an overall conclusion of the work.

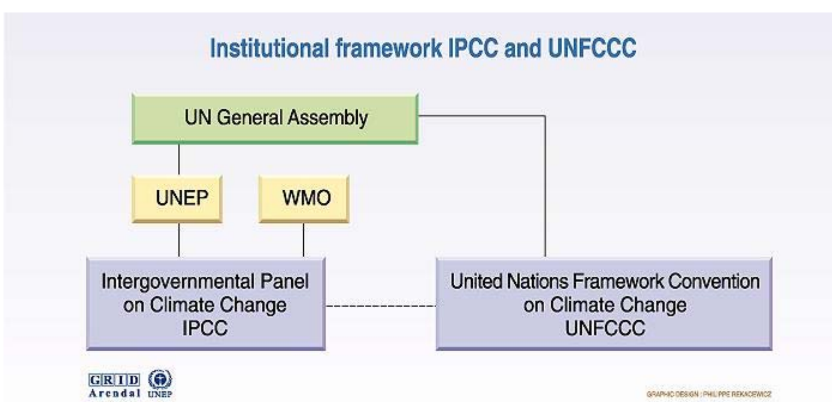
2 Outstanding international climate policy: the Kyoto Protocol

The Kyoto Protocol to the United Nations Framework Convention on Climate Change (Kyoto Protocol), consisting of one Preamble, 28 Articles, and two Annexes, represents much more than an international legal agreement. It can be regarded as one of the most ambitious and far-reaching agreements on environmental issues for the last decades, leading to a public awareness of the fact that climate change can no longer be ignored.

2.1 The way to the Protocol

Human interference with the climate became an issue for the very first time in 1979 at the First World Climate Conference. Public concern about environmental issues continued to increase during the 1980s, when governments grew progressively more aware of climate issues.

In 1988, the governing bodies of the ‘World Meteorological Organization’ (WMO) and the ‘United Nations Environment Programme’ (UNEP) created a new body, the ‘Intergovernmental Panel on Climate Change’ (IPCC), to assess scientific information on the subject (see Figure 2). In 1990, the IPCC issued its First Assessment Report, confirming that the threat of climate change was evident (GRUBB *et al.*, 1999, p. 5).



Source: United Nations framework convention on climate change (UNFCCC).

Figure 2: Overview of the institutional IPCC and UNFCCC framework (UNEP, 2004-07-23).

The 'United Nations Framework Convention on Climate Change' (UNFCCC) was established in May 1992, after merely 15 months of negotiations. At the Rio de Janeiro 'United Nations Conference on Environment and Development' (UNCED or 'Earth Summit') of June 1992, the new Convention was opened for signature and entered into force in March 1994. Up to now[1], the Convention has been joined by the European Community and further 188 states. This almost worldwide Convention is one of the most universally supported of all international environmental agreements (UNFCCC, 2003, pp. 3-4; OBERTHÜR and OTT, 1999, p. 33).

The intention of the Convention is described in Article 2 of the Convention text:

> *The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner* (UN, 1992, p. 9).

Since it entered into force in 1994, the Parties to the Convention, which are those countries who have ratified, accepted, approved, or acceded the treaty, have been holding annual meetings, the so-called 'Conference of the Parties' (COP). They meet to monitor its implementation and continue talks on how to tackle the threat of climate change. Successive decisions taken by the COP now make up a detailed set of rules for practical and effective implementation of the Convention.

Even as they adopted the Convention, however, governments knew that its provisions would not be sufficient to tackle the climate change. At the first Conference of the Parties (COP 1) held in Berlin in early 1995 a new round of talks, known as the Berlin Mandate, was launched in order to discuss firmer, more detailed commitments for industrialised countries.

In December 1997, after two and a half years of intensive negotiations, the Kyoto Protocol was adopted as a substantial extension to the UNFCCC at COP 3 in Kyoto, Japan (see

[1] See also the current list of member states available at http://unfccc.int/resource/conv/ratlist.pdf (2004-10-07).

UNFCCC, 1998). It contains quantified, legally binding commitments to reduce greenhouse gas (GHG) emissions and requires a separate, formal process of signature and ratification by national governments to enter into force (UNFCCC, 2003, pp. 3-4).

2.2 Essential components

While the Convention concerns all greenhouse gases not covered by the 1987 Montreal Protocol, the Kyoto Protocol focuses on the following six greenhouse gases (UNFCCC, 2003, p. 2):

- Carbon dioxide (CO_2),
- Methane (CH_4),
- Nitrous oxide (N_2O),
- Hydrofluorocarbons (HFCs),
- Perfluorocarbons (PFCs),
- Sulphur hexafluoride (SF_6).

The first three gases are estimated to account for 50, 18, and 6 percent, respectively, of the overall global warming effect arising from human activities.

To measure how each of the greenhouse gases contributes to the global warming effect, the ‘global warming potential’ (GWP) is introduced. It is a measurement to show how much of a given mass of a greenhouse gas contributes to the global warming effect in a certain period (e.g. 100 years).

The following Figure 3 gives an overview of the GWP and the lifespan of relevant greenhouse gases:

The main greenhouse gases

Greenhouse gases	Chemical formula	Pre-industrial concentration	Concentration in 1994	Atmospheric lifetime (years)***	Anthropogenic sources	Global warming potential (GWP)*
Carbon-dioxide	CO_2	278 000 ppbv	358 000 ppbv	Variable	Fossil fuel combustion Land use conversion Cement production	1
Methane	CH_4	700 ppbv	1721 ppbv	12,2 +/- 3	Fossil fuels Rice paddies Waste dumps Livestock	21 **
Nitrous oxide	N_2O	275 ppbv	311 ppbv	120	Fertilizer industrial processes combustion	310
CFC-12	CCl_2F_2	0	0,503 ppbv	102	Liquid coolants. Foams	6200-7100 ****
HCFC-22	$CHClF_2$	0	0,105 ppbv	12,1	Liquid coolants	1300-1400 ****
Perfluoromethane	CF_4	0	0,070 ppbv	50 000	Production of aluminium	6 500
Sulphur hexa-fluoride	SF_6	0	0,032 ppbv	3 200	Dielectric fluid	23 900

Figure 3: The main greenhouse gases (UNEP, 2004-07-23).

Before the Kyoto Protocol is ready to enter into force, at least 55 Parties to the Convention need to ratify, assuming that these accounted for at least 55% of the total carbon dioxide emissions in 1990 (see Figure 4).

This regulation makes sure that no single Party may block the entry into force of the Kyoto Protocol (UNFCCC, 2003, p. 16). Due to the fact that the USA – responsible for the emission of 36.1% greenhouse gases in 1990 – have voted against ratification of the Kyoto Protocol, its future depends on the decision of other key emitters like the Russian Federation or Australia.

Emissions of Annex I Parties (1990)

Annex I Party carbon dioxide emissions in 1990 and their share of the total for the purpose of determining entry into force of the Kyoto Protocol

Party	1990 CO_2 emissions (Gg)	%
Australia	288,965	2.1
Austria*	59,200	0.4
Belgium *	113,405	0.8
Bulgaria	82,990	0.6
Canada	457,441	3.3
Czech Republic	169,514	1.2
Denmark*	52,100	0.4
Estonia	37,797	0.3
Finland*	53,900	0.4
France*	366,536	2.7
Germany*	1,012,443	7.4
Greece*	82,100	0.6
Hungary	71,673	0.5
Iceland	2,172	0.0
Ireland*	30,719	0.2
Italy*	428,941	3.1
Japan	1,173,360	8.5
Latvia	22,976	0.2
Liechtenstein	208	0.0
Luxembourg*	11,343	0.1
Monaco	71	0.0
Netherlands*	167,600	1.2
New Zealand	25,530	0.2
Norway	35,533	0.3
Poland	414,930	3.0
Portugal*	42,148	0.3
Romania	171,103	1.2
Russian Federation	2,388,720	17.4
Slovakia	58,278	0.4
Spain*	260,654	1.9
Sweden*	61,256	0.4
Switzerland	43,600	0.3
United Kingdom*	584,078	4.3
USA	4,957,022	36.1
*15 European Community member states combined		24.2

The table does not include Annex I Parties that had not yet submitted a national communication under the Convention when the Protocol was adopted. The emissions of these Parties will not be counted towards the entry into force threshold. Figures exclude the land-use change and forestry sector.

Figure 4: Greenhouse gas emissions of the Annex I Parties at the 1990 baseline (UNFCCC, 2003, p. 15).

The Russian Federation, responsible for 17.4% of the overall emissions, rejected its ratification mainly for economic reasons for a fairly long period (see POKROVSKY and ALLAKHVERDOV, 2004; MOSCOW TIMES, 2004-08-20), but recently approved the Kyoto Protocol (BBC, 2004-10-06). On November 5th, 2004 president Putin after many years of negotiations finally signed the Kyoto Protocol, which is now complete and will be brought into force in February 2005 (see GUARDIAN, 2004-11-05).

The heart of the Kyoto Protocol is its legally binding reduction targets for the industrialised nations to reduce their emissions of greenhouse gases by an average of 5.2% (from the baseline of 1990) within 2008 and 2012 (the so-called first commitment period). All Parties have individual emission targets, which were determined in Kyoto after intensive negotiations and are listed in the Protocol's Annex B (see Figure 5).

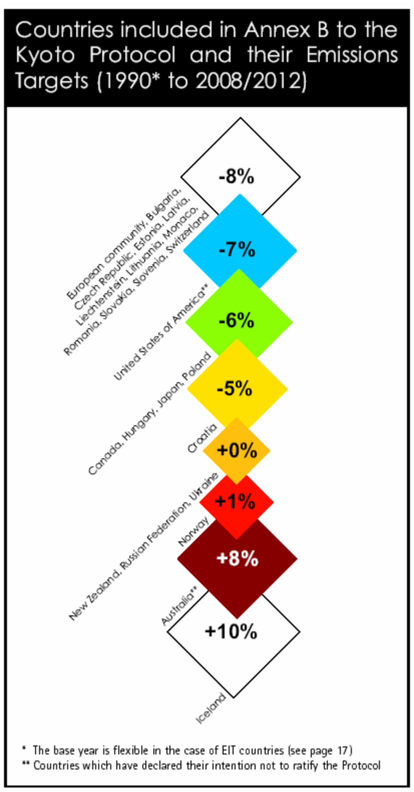


Figure 5: Emission reduction targets of several countries (UNFCCC, 2003, p. 25).

The 15 member states of the European Community agreed to take advantage of a calculation under the Protocol, known as a 'bubble', to redistribute their overall reduction targets among themselves in a proportional way. As a result of this 'burden sharing agreement', Austria's emission target for the first commitment period is a reduction of 13% to the baseline of 1990 (UNFCCC, 2003, p. 17).

The Convention separates countries into three main groups according to their different commitment status (UNFCCC, 2003, pp. 5-6):

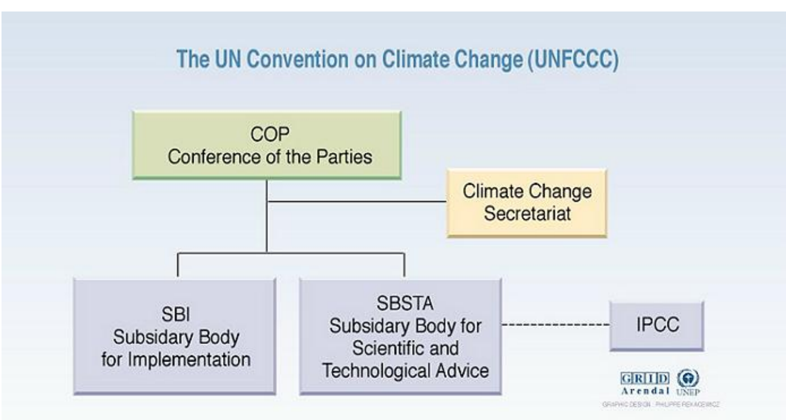
Annex I Parties include industrialised countries that were members of the OECD (Organisation for Economic Co-operation and Development) in 1992, plus countries with economies in transition (the EIT Parties), including the Russian Federation, the Baltic States, and several Central and Eastern European States.

A prerequisite for Annex I Parties is that they must adopt climate change policies with the aim of reducing their greenhouse gas emissions to the 1990 baseline by the year 2000. The Convention grants the Parties of economies in transition *'a certain degree of flexibility'* in implementing commitments, taking into account their specific situation of economic changes that led to big cuts in emissions.

Annex II Parties consist of all OECD member countries. They are required to provide financial aid to enable developing countries to undertake emission reduction activities. Furthermore, they are asked to *'take all practicable steps'* to promote the development and transfer of environmentally friendly technologies to economies in transition Parties and developing countries.

Non-Annex I Parties mainly consist of developing countries, some of them being especially vulnerable to the harmful impacts of climate change (e.g. countries with low-lying coastal areas as well as countries that rely on fossil fuel production and commerce). For those countries, the Convention emphasises special activities such as investment, insurance and technology-transfer.

The Conference of the Parties is the supreme and ultimate decision-making body of the Convention, convening each year (UNFCCC, 2003, p. 7). It is complemented by two subsidiary bodies, the 'Subsidiary Body for Implementation' (SBI) and the 'Subsidiary Body for Scientific and Technological Advice' (SBSTA), preparing work for the COP and meeting at least twice a year (see Figure 6).



Source: United Nations framework convention on climate change (UNFCCC).

Figure 6: The organisational framework of the UNFCCC (UNEP, 2004-07-23).

The Parties agreed that the COP would serve as Meeting of the Parties to the Protocol (COP/MOP) in conjunction with the first session of the COP after entry into force of the Kyoto Protocol (UNFCCC (a), 2004-07-23).

The Secretariat, also known as the Climate Change Secretariat, has been hosted by the German Government in Bonn since 1996. Moreover, it is shared by the Convention and the Kyoto Protocol (UNFCCC (b), 2004-07-23). Its main tasks are making practical arrangements for sessions of the Convention bodies, assisting the Parties in implementing their commitments, providing support to on-going negotiations and coordinating with the Secretariats of other relevant international bodies, amongst those notably the ‘Global Environment Facility’ (GEF) and the IPCC. Further specific tasks of the Secretariat include the preparation of official documents for the COP and subsidiary bodies, the coordination of in-depth reviews of Annex I Party national communications and the compilation of greenhouse gas inventory data.

2.3 Sinks and sources

A controversial item of the negotiation process was the debate about sinks and sources of greenhouse gases. Sinks are ecosystems, which are able to remove carbon dioxide from the atmosphere by absorbing and storing it over a long period of time (PEWCLIMATE (a), 2004-07-23). In terms that are more general, sinks can be regarded as any activity or mechanism that results in the net removal of greenhouse gases, aerosols, or precursors of greenhouse gases from the atmosphere. Nevertheless, the presence of biological sinks and especially their quantification is subject to substantial uncertainties (PEWCLIMATE (b), 2004-07-23). Particularly for these reasons, the inclusion of sinks in national greenhouse gas balances led to heavy discussion during the Kyoto follow-on negotiations.

A compromise was found in Bonn in 2001 and the Protocol was eventually finalised for ratification at COP 7 in Marrakesh in 2001.

2.4 Kyoto mechanisms

To supplement domestic greenhouse gas mitigation of Annex I Parties, four sophisticated mechanisms have been developed to reduce emissions in other countries (UNFCCC, 2003, p. 18-22). These flexible mechanisms consist of Joint Implementation (JI; Article 6 of the Kyoto

Protocol), which are sink projects in third-party countries, and Clean Development Mechanisms (CDM; Article 12 of the Kyoto Protocol), which are projects in Non-Annex I countries. Both mechanisms have in common that the achieved reduction can be claimed for the national greenhouse gas inventories respectively. Another mechanism is called Emissions Trading (ET; Article 17 of the Kyoto Protocol), which permits the transfer of emission reduction units. Furthermore, the 'bubble policy' is the fourth international instrument, which allows a redistribution of reduction targets among communities of states. This mechanism is currently applied by the EU member states, with the aim of an overall reduction of 8% with single countries having different proportional commitments (see OBERTHÜR and OTT, 1999).

2.5 Reviewing and reporting

One central point of international agreements is the reviewing and reporting process to guarantee compliance with negotiated regulations. In the Kyoto context, the issue of reporting is following the UNFCCC practice and is addressed by guidelines for preparing national communications[2] (UNFCCC, 2003, p. 9). The Parties to the Convention up to now had to submit three national communications, the fourth being delivered up to 1st January of 2006. Annex I Parties, for whom exist more stringent regulations than for Non-Annex I Parties, additionally have to submit greenhouse gas inventories on an annual basis, also containing all emissions and removals arising from land use, land-use change and forestry (LULUCF) activities. This documentation then has to undergo an in-depth expert review process ranging from technical reviews to in-country visits.

2.6 The sector Land Use, Land-Use Change and Forestry

Articles 3.3 and 3.4 of the Kyoto Protocol refer to human-induced changes of sinks in the land use, land-use change and forestry sectors. The idea behind it is that several activities that have been removing greenhouse gases from the atmosphere since 1990 (namely *afforestation* and *deforestation*) may also be used to contribute emission targets of the Parties. Nevertheless, all

[2] See also further information on reporting guidelines for annual inventories and guidelines for reporting on global climate observing systems for Annex I Parties at http://unfccc.int/cop7/issues/natcompartan1.html (2004-09-16).

actions that reduce forests (*deforestation*) have to be subtracted from the emission balances of the Parties (UNFCCC (c), 2004-07-26).

The rules for LULUCF are laid out in the Marrakesh Accords and allow the Parties to choose whether to account for *forest management, cropland management, grazing land management* or *revegetation*. The Parties must choose from the different activities they want to use to meet their emission targets by the end of 2006. After that, their choice is binding for the first commitment period. The following is a definition of eligible LULUCF activities (UNFCCC, 2002, p. 58):

> (a) '*Forest'* is a minimum area of land of 0.05-1.0 hectares with tree crown cover (or equivalent stocking level) of more than 10-30 per cent with trees with the potential to reach a minimum height of 2-5 metres at maturity *in situ*. A forest may consist either of closed forest formations where trees of various storeys and undergrowth cover a high proportion of the ground or open forest. Young natural stands and all plantations which have yet to reach a crown density of 10-30 per cent or tree height of 2-5 metres are included under forest, as are areas normally forming part of the forest area which are temporarily unstocked as a result of human intervention such as harvesting or natural causes but which are expected to revert to forest;
>
> (b) '*Afforestation'* is the direct human-induced conversion of land that has not been forested for a period of at least 50 years to forested land through planting, seeding and/or the human-induced promotion of natural seed sources;
>
> (c) '*Reforestation'* is the direct human-induced conversion of non-forested land to forested land through planting, seeding and/or the human-induced promotion of natural seed sources, on land that was forested but that has been converted to non-forested land. For the first commitment period, reforestation activities will be limited to reforestation occurring on those lands that did not contain forest on 31 December 1989;
>
> (d) '*Deforestation'* is the direct human-induced conversion of forested land to nonforested land;
>
> (e) '*Revegetation'* is a direct human-induced activity to increase carbon stocks on sites through the establishment of vegetation that covers a minimum area of 0.05 hectares and does not meet the definitions of afforestation and reforestation contained here;
>
> (f) '*Forest management'* is a system of practices for stewardship and use of forest land aimed at fulfilling relevant ecological (including biological diversity), economic and social functions of the forest in a sustainable manner;
>
> (g) '*Cropland management'* is the system of practices on land on which agricultural crops are grown and on land that is set aside or temporarily not being used for crop production;
>
> (h) '*Grazing land management'* is the system of practices on land used for livestock production aimed at manipulating the amount and type of vegetation and livestock produced.

As can be seen from the abovementioned, a common definition for the term ‘forest’ has been established in order to provide comparability and consistency[3]. Some flexibility is allowed to consider national circumstances: country-specific values can be chosen for definition, but this choice has to be made before the first commitment period, these values have to be consistent over time and may not be changed subsequently.

The topic of LULUCF and further implications for national greenhouse gas inventories is further discussed in Chapter 4.

[3] An investigation of multiple definitional scenarios of these terms can be found in IPCC (2000b, pp. 141-144).

3 Remote sensing and the Kyoto Protocol

3.1 Introduction

The scientific community has undertaken several efforts to tackle the challenge of climate change in the past. In conjunction with the rapidly developing field of information technologies, it can be stated that, amongst other techniques, remote sensing is one of the most beneficial tools for collecting geo-spatial data to better understand the great number of causes for climate change and modelling to the impacts and consequences for future life on earth.

Currently remote sensing comprises a wide range of applications from landscape characterisation and urban planning to wildlife monitoring, from military services to applications as diverse as weather forecasting and location based services. Talking of supplying techniques for the Kyoto Protocol, certain groups of systems can be considered as being valuable for land surface monitoring, as can be seen in Table 1 on the next page.

In the following section, a short review of selected techniques that are associated with the Kyoto Protocol shall be given.

Table 1: Selected Earth Observation systems for mapping and monitoring the Earth's land surface (adapted from KRAMER, 1996; WAGNER and JONAS, 2003, p. 42)

System Category	Physical characteristics	Satellite & Instrument	Status	Spatial resolution	Temporal sampling	Target information
Airborne Systems						
Aerial Photography	optical & NIR, mono & stereo	Zeiss	Op.	1 - 10 cm	3 - 10 years	Type and structure of land cover classes
Laserscanning	single pulse & full waveform	Optech, Riegl	Dem.	0.1 - 1 m	3 - 10 years	Topography, vegetation structure
Synthetic Aperture Radar	multi-frequency, multi-polarisation microwaves	ESAR	Exp.	1 - 10 m	5 - 10 years	Land cover, biomass
Hyperspectral Imaging	> 100 spectral bands, optical and IR	HYMAP	Exp.	5 - 10 m	5 - 10 years	Land cover, biomass, soil classes
Satellite Imaging Systems						
Very-high resolution Optical Imaging	few and broad spectral bands, optical & NIR	IKONOS, QuickBird	Dem.	0.5 - 5 m	1 - 5 years	Land cover
Multi-spectral Imaging	optical and IR	Landsat, SPOT, ASTER	Op.	10 - 20 m	season - 1 year	Land cover
Synthetic Aperture Radar	single-frequency microwaves, interferometry	ERS, ALOS, ENVISAT	Dem.	10 - 50 m	season - 1 year	Biomass, land cover
Satellite Monitoring Systems						
Wide-swath Multi-spectral Scanners	optical and IR	AVHRR, MODIS	Op.	0.25 - 1 km	week - month	Vegetation phenology
Microwave Radiometers	multi-frequency passive measurements	SSM/I, AMSR	Dem.	10 - 80 km	Day	Land surface hydrology (snow)
Microwave Scatterometers	multi-look, single frequency Radars	ERS, METOP	Dem.	20 - 50 km	Day	Land surface hydrology (soil moisture)
Geostationary Radiometers	optical and IR	METEOSAT, MSG	Op.	1 - 10 km	15 min	Clouds, land surface energy balance
Atmospheric Sounders	optical, IR and microwave sounders	METOP, HIRS, MHS	Op.	10 - 20 km	Day	Atmospheric temperature, humidity

Legend: Op. = Operational, Dem. = Demonstrated, Exp. = Experimental.

3.2 Overview of remote sensing technologies relating to the Kyoto Protocol

Remote sensing in international environmental policy

Serving as a good starting point, DE SHERBININ (2002) gives a short overview of the power of remote sensing and its capabilities in international environmental policy. The paper states that remote sensing is used due to parallel developments in Earth observation and international environmental diplomacy. As the number of international environmental treaties is rising continuously, the need for monitoring their compliance is growing, too. As one example of the successful use of remote sensing as a compliance tool, DE SHERBININ refers to the Bonn Agreement, which is an international programme to monitor marine oil spills signed by the nations bordering the North Sea. When talking about the Kyoto Protocol, DE SHERBININ (2002, pp. 3-4) refers to the ability of remote sensing not for fully compiling greenhouse gas inventories but for serving valuable information on agricultural and forest land, which are important carbon sources and sinks. He also refers to international programmes such as the GMES initiative (Global Monitoring for Environment and Security) and others (see GMES, 2004-08-24) in which remote sensing plays a major role.

WULDER and FRANKLIN (2003, p. 3) report of a current transition of remote sensing from *data preparation* to *information generation,* which they put down to parallel developments in technological advances, data processing, and information synthesis. They also speak of a *'democratisation of geospatial information',* meaning that not only the producer of the data, but increasingly stakeholders like non-governmental organisations use remotely sensed information. The publication of WULDER and FRANKLIN (2003) furthermore can serve as an excellent overview of case studies in the forestry sector.

One of the few studies that scrutinise remote sensing techniques explicitly in light of the Kyoto-process is the review of ROSENQVIST *et al.* (2003a), which demonstrates that remote sensing plays an important role in several ways. When talking about the 1990 baseline mapping, the authors demonstrate that only Landsat TM and SPOT High Resolution Visible were operational in 1990 and that among Radar sensors (Radio Detection and Ranging), no active microwave systems were in operation in 1990. This led to solutions that data of subsequent sensors have been backdated to generate a 1990 baseline. Furthermore, the detection of land cover is a challenging task, as the approaches of countries in selected biota vary in definition of crown closure. Therefore, also the classification of ‘forest’ or ‘non-forest’ varies from country to country (ROSENQVIST *et al.*, 2003a, p. 445). In terms of biomass quantification, remote sensing holds great potential, although *‘no studies have yet presented a technique that is consistent, reproducible and applicable at regional or continental scales’* (ROSENQVIST *et al.*, 2003a, p. 446). The paper also reports on inequalities in the accessibility of remote sensing-data, which could be overcome by a closer collaboration between countries that have strong expertise and those who do not. The authors conclude that remote sensing is regarded as not yet operational *‘in more than a handful of applications relevant to the Kyoto Protocol’*. They outline topics for further research such as the fusion of optical data and SAR data (Synthetic Aperture Radar), synergies between Lidar (light detection and ranging) and other sensors, as well as the development of applications for SAR interferometry (ROSENQVIST *et al.*, 2003a, p. 449; p. 451).

Mapping the 1990 Kyoto baseline

Landsat TM is one of the very few sensors, which were available at the 1990 Kyoto baseline. This fact forms the basis of a number of investigations. Amongst these is the work of WALLACE *et al.* (2004), a research paper from the field of ecology and remote sensing. The authors call for quantitative monitoring systems with repeatable data and analysis methods. WALLACE *et al.* (2004) give examples of Australian operational monitoring programmes, mainly Landsat-based programmes and relevant AVHRR (Advanced Very High Resolution Radiometer) programmes, where the choice of data has been met because of temporal and spatial requirements on the 1990 Kyoto baseline.

Another study with Landsat data was conducted by GOODENOUGH *et al.* (2001) in order to estimate aboveground carbon for a test-site in Canada. Compared with National Forest Inventory data, the remote sensing classification showed almost twice the amount of forest with half the biomass per hectare. Accuracies could be reduced by using leaf-on/leaf-off-paired images (GOODENOUGH *et al.*, 2001, p. 765).

Retrieval of bio-geophysical parameters

Several programmes deal with the derivation of bio-geophysical parameters from remote sensing data. They use e.g. ecosystem models that integrate remote sensing images, climate data, soil types, and forest inventory. Thus specific data parameters of the carbon budget like 'net primary productivity' (NPP) or 'leaf area index' (LAI) can be derived. The derivation of these parameters can lead to a better scientific understanding of the carbon cycle up to source and sink maps of whole forest biomes, as CHEN *et al.* (2003, p. 637) show.

Furthermore, lively scientific discussion on the sink/source question is held, because of still pertaining variability in data and uncertainty in estimation of carbon pools. For instance, VALENTINI *et al.* (2000, p. 864) examined 15 European forests and showed that in higher latitudes the constitution of boreal soils differ largely from temperate soils with respect to their amount of soil organic matter and carbon content.

The Normalized Difference Vegetation Index (NDVI) captures the contrast between red and near-infrared reflection of radiation and is thus an indicator of green leaf area. DONG *et al.* (2003) investigated NDVI datasets, which cover the period from 1981 to 1999 and draw the following picture. Eurasian boreal and North American temperate forests act as carbon pools, whereas some Canadian boreal forests denote carbon losses. Moreover DONG *et al.* show differences up to 50% for total biomass between remotely sensed estimates and forest inventory estimates, which according to them occur due to residual atmospheric effects and unequal forest inventory estimates (DONG *et al.*, 2003, p. 408).

In the field of microwave satellite systems the techniques of Radar and Lidar hold great potential for biomass retrieval. Those sensors send out short electromagnetic pulses in the range of 1-10 GHz and measure the backscattered echoes. ROSENQVIST *et al.* (2003b) describe the 'Kyoto & Carbon Initiative' as an approach to support global carbon cycle science with L-band SAR and a multi-spectral scanner. The *'retrieval of above-ground biomass stocks is a Holy Grail for carbon budget research'* (ROSENQVIST *et al.*, 2003b, p. 1475), which means that the quantification of biomass is not an explicit Kyoto Protocol requirement but necessary for quantification of afforestation and deforestation events. The study addresses the provision of systematic observations using a planned L-band SAR with an effective ground resolution of 20-100 metres, therefore meeting the Kyoto Protocol implications.

Studies like LIM *et al.* (2003, p. 101) show that Lidars can map forest parameters and contribute significantly to forest inventories. OLSSON (2004, p. 133) even reports the operational status of this method in Norway. However, the knowledge to provide applications for forest industry is still in a development stage.

International research co-operation

Scientific groups all over the world participate in programmes of international space agencies. A specific programme of the European Space Agency (ESA) is the 'Data User Element' (DUE), with the objective '*to encourage the establishment of a long-term relationship between user communities and Earth Observation'* (ESA (b), 2004-10-27). One of the projects participating in the DUE programme is the 'Kyoto Inventory' project, quoted by VOLDEN *et al.* (2003) and ROMERO *et al.* (2004). The five European countries Finland, Italy, The Netherlands, Norway, and Switzerland examine the potential of remote sensing for evaluating land use and land-use change for the Kyoto Protocol reporting. Therefore, they define user-requirements for determining land use, assessing forest areas, estimating aboveground biomass etc., at a minimum spatial resolution for mapping 0.5 ha (thus meeting the Kyoto Protocol requirements). At first, minimum requirements are outlined, comprising transparency, reliability and periodicity of data. In addition, a high degree of automation without terrestrial control is desired (ROMERO *et al.*, 2004, p. 129). By using optical imagery (Landsat TM and SPOT) and Radar imagery (ERS SAR and Envisat Advanced Synthetic Aperture Radar ASAR) a series of products is derived and validated by using 12 representative test sites spread over Europe (VOLDEN *et al.*, 2003, p. 4583). As a result, due to data requirements the sensor Landsat TM is identified. In accordance with the *GPG-LULUCF*, six land-use categories are derived and compared with aerial photos and topographic maps. First results show, that the detected forest area tends to be overestimated and in addition problems with small and sparsely vegetated forests are encountered (ROMERO *et al.*, 2004, p. 130).

Another international initiative in a similar context is the ‘geoland’ project. Being an integrated part of the GMES initiative (Global Monitoring of Environment and Security), led by the European Union and ESA, its aim is to present operational capabilities in the area of land cover and vegetation (LEROY *et al.*, 2004, p. 783).

The on-going EU project ‘SIBERIA II’ strives for full carbon accounting over Northern Eurasia, where a palette of sensors (passive/active microwave and optical sensors) together with dynamic vegetation models is used to calculate biophysical parameters. This leads to a variety of data-sets considering land cover products, freeze/thawing cycles, wetland monitoring, forest fires as disturbances of carbon budget, vegetation phenology, and wetland monitoring (see SCHMULLIUS and HESE, 2003).

Hence, for a non-exhaustive list of international projects the reader is referred to a section in *GPG-LULUCF*, where further international programmes are presented (IPCC, 2003, pp. 5.73-5.75).

Moreover, it can be observed that an increasing number of scientific institutions and commercial vendors are planning to develop small-sized platforms (‘smallsats’), which are highly specific to their own applications and requirements. The launch of these micro-satellites is advantageous in order to reduce overall costs, thus they serve exactly the scientific needs of their owner organisation. Examples for those technology-demonstrators are BIRD, the micro-satellite of the German Aerospace Centre on ‘Bi-spectral Infrared Detection’, and DEMETER, the French satellite ‘Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions’ (see BIRD, 2004-08-24; DEMETER, 2004-08-24).

ESA also has reacted to the growing community of users in the public and private sectors and therefore has established its 'Living Planet Programme'. This programme involves shorter and more focussed missions by using smaller satellites like CryoSat (a Radar altimetry mission dedicated to the observation of the polar regions) or SMOS (Soil Moisture and Ocean Salinity mission). Thus, a better response to user needs is achieved (see ESA (a), 2004-11-09).

The abovementioned developments demonstrate that it is possible to bring together users in public and private sectors as well as space industry. Time will show whether it is possible to develop missions that foster the Kyoto Protocol requirements.

3.3 Current situation of forest inventories and remote sensing

Based on the findings in IPCC (2000b, p. 31), it can be stated that forest biomes play an important role in the global carbon cycle. They cover approx. one third of the land surface and account for about 77% of the plant carbon and about 40% of the soil carbon[4]. Therefore, the detection of changes in forests is significant for greenhouse gas balances and can be carried out with remote sensing methods.

European level

Having a closer look on Europe, LAITAT *et al.* (2000, p. 243) evaluate the contribution of European countries to a *'commonly agreed C-accounting system'* in order to strengthen Europe's competence at a high international level. They quote results of the on-going 'COST E21' programme, which is an intergovernmental framework in the field of scientific and technological research, focused on European forest inventories and their greenhouse gas balances[5]. The paper gives an interesting overview of 16 national forest inventories (NFIs) of selected European countries showing a highly variable spectrum of forest inventories across the states, mainly due to different time intervals and accuracy levels (see Table 2 on next page).

As can be seen in Table 2, merely 2 out of 16 states, namely Switzerland and Finland, use satellite imagery for assessing their forest inventory, whereas 10 out of 16 evaluated countries use aerial photographs. The authors conclude that the key problem is, that all inventories were made for calculating profit-making stem-volume and not for reporting carbon values, leading to major discrepancies. Furthermore, there is insufficient information on conversion factors for deriving CO_2-emissions out of timber volume.

[4] Soil carbon pools are considered down to a depth of 1 m.
[5] See also http://www.bib.fsagx.ac.be/coste21/ (2004-10-08) for further details.

Table 2: Characteristics of selected National Forest Inventories in European countries (adapted from LAITAT *et al.*, 2000, p. 245).

Country	AT	BE	CH	DE	DK	ES	FI	FR	GB	GR	HU	HR	IS	NL	NO	SE
Start	1961	1980 1994[1]	1983	1986	1981	1964	1921	1960	1924	1963	1950's	1998	1972	1940	1919	1923
Periodicity (year)	5	10	10	15	10	20-10	<10	10-12	15-20	30	Cont.[2]		15	5	5	1(5)
Forest surface area (in 1000 ha)	3.924	682	1.234	10.740	538	25.984	22.768	16.989	2.489	6.513	1.811	621	131	339	12.000	30.259
Grid (in km)	4x4	1x0.5	1.4x1.4 0.5x0.5	4x4	-	1x1	6x6	various	various	1x0.5	Comp.[3]		-		3x3	3x3[4] (30x30)
Plots	11,000	10,600	6,500	12,580	-	84,203	70,000	133,500		2,744	-		-	3,400	10,500	18,000
Level	N	SN	N	N	N	N	N	N	SN	N	N	N		N	N	N
Inventory	F	F	A,F,S	F	Q	F,A	F,A,S	F,A	A,F	F,A	F,A	F,A	F,A	F,Q	F	F,A
Percentage standard error (in area)	1.2	0.42	0.30	1.10	N.A.	N.A.	0.48	0.71	3-15	0.2	N.A.	1.0	N.A.	N.A.	0.96	0.50
Percentage standard error (in volume)	1.6	5.1	1.0	0.80	N.A.	0.85 1.13[5]	0.57	0.54	1-15	2.6	N.A		N.A.	5	1.36	0.60
Percentage standard error (in volume growth)	N.A.	N.A.	0.90	N.A.	N.A.	N.A.	0.80	0.59	N.A.	N.A.	N.A.		N.A.	N.A.	1.40	0.40
Wood volume	MS	MS	MS	Other[6]	M	MS	MS	MS	MS	MS	Other[7]		MS	MS	MS	MS
Above ground	B		B	B,C		N.A.	N.A.	N.A.	N.A.	N.A.	B,C		C	N.A.	N.A.	B,C
Below ground	SC	N.A.	N.A.	RM,SC	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	SC		RM,SC	N.A.	SC	RM,SC
Expansion factors	D2, N	D1, DS	N	N[8]	D1,N	N	N	D2,N	N.A.	D1	D1,N		N	D1,N	N[9]	N

Country codes: AT = Austria, BE = Belgium, CH = Switzerland, DE = Germany, DK = Denmark, ES = Spain, FI = Finland, FR = France, GB = United Kingdom, GR = Greece, IR = Ireland, IS = Iceland, NL = The Netherlands, NO = Norway, SE = Sweden.
Level of forest inventories: N = national-, SN = sub-national-level.
Inventory: F = using field surveys, A = aerial photographs, S = satellite imagery, Q = questionnaire.
Wood volume: MS = marketable stemwood or total bole volume over bark and/or under bark.
Biomass values: B = aboveground biomass, C = carbon, RM = root biomass, mostly coarse roots, SC = soil carbon.
Expansion/conversion factors: D1 = default values from IPCC, D2 = default values from other European countries, N = derived from national data.
N.A. = non assessed; (-) = not relevant; ( ) = not communicated.

[1] Respectively for the Walloon and Flemish regions.
[2] Continuous inventory, in which approximately one-tenth of the forest is surveyed.
[3] The unit of the survey is the forest compartment (administrative blocks).
[4] Grid is 3x3 to 15x15 km on random plots and 7x7 to 30x30 km on permanent plots. The density of the grid decreases from the South to the North.
[5] Respectively for conifers and for deciduous.
[6] Wood diameter > 7 cm (including coarse branches).
[7] Total aboveground volume including fine branches and leaves.
[8] Derived from in-depths studies, not from the NFI.
[9] Soil samples carried out on a sub-sample of the NFI plots.

SCHUCK *et al.* (2003) compiled a European-wide forest proportion map by calibrating AVHRR data with national forest inventories. The comparison of the inventory statistics with the AVHRR classified data shows major national-specific differences, a fact that is put down to the differences in the national forest inventories and definitions of 'forest' (SCHUCK *et al.*, 2003, p. 198).

The status of remote sensing and forest inventories in the United Kingdom is well described in the study of PATENAUDE (2003). Being part of a yearly-performed evaluation, it presents a valuable overview of the employed technologies with a critical review of their potential to fulfil UK-specific requirements for inventorying. Main findings are that remote sensing is currently not operational for biomass estimation at large scale and that the availability of sensors is limited to extensive costs (PATENAUDE, 2003, p. 9:28).

The *GPG-LULUCF* (IPCC, 2003, pp. 4.101-4.103) introduces two different approaches for aboveground biomass estimation, the *direct approach* and the *indirect approach*. The *direct approach* uses the average diameter at breast height (dbh) of trees in sample plots as input of biome-specific allometric equations. The *indirect approach*, first measures the commercial volume of trees, either through field instruments (e.g. relascope) or through using locally derived equations. Afterwards this value is converted to the biomass by using biomass expansion factors. The gained biomass value additionally contains tree components such as branches and leaves. Additional reference to literature, as well as sample equations, is given for both approaches in the text. The estimation of belowground biomass is not well established yet and remains a challenging task. Current solutions base on the use of 'belowground to aboveground dry biomass ratios', but, as literature reviews show, these ratios are not yet standardised and may not apply to plantations as they differ too much from native forests.

Situation in Austria

Remote sensing-methods in Austria can be stated as following a combined approach, but let us have a closer look. The Austrian 'National Forest Inventory' (NFI) is based on a sampling procedure with a systematic distribution of a sampling grid (SCHIELER and HAUK, 2001, p. 3). With a distance of 3.89 km, the sampling grid points are distributed regularly over the entire state territory, with 4 sample plots of 300 m^2 at each corner. This results in a total number of 11,000 inventory plots. The plots are geo-referenced using GPS and are therefore easily to detect. Inventories have been carried out from 1961 to 2002. For each sampling plot, key parameters like forest area, growing stock, species composition, biomass components, and structural parameters are assessed. By using indices, which were derived from national statistics, the annual increment and harvest can be calculated. In addition, conversion factors are used to calculate carbon rates according to tree species and age class composition (see SCHIELER and HAUK, 2001). Finally, through statistical sampling methods, the total area of forest can be stratified and derivates like forest-maps are presented[6].

One of the few assessments of Austria's 'Article 3.3-potential' (afforestation, reforestation, deforestation) has been carried out by WEISS *et al.* (2000). At the time of that study, the terms 'forest', 'afforestation', 'reforestation', 'deforestation' and the exact modus of carbon accounting had not yet been defined. That is why the authors considered a potential range of options. They employed different carbon accounting scenarios and definitions, which resulted in different carbon sink/source estimates for biomass and soils. The main findings of WEISS *et al.* (2000) were that the Austrian forests in 1990 symbolised a carbon-stock of 320±42 Mt C for biomass. Including soils to a depth of 50 cm the carbon-stock even came up to 463±185 Mt C. These stocks represent about 40 times the Austrian CO_2 equivalents of greenhouse gas emissions, and account for nearly 47% of Austrian's area. These facts underline the importance of Austrian forests acting as carbon sinks (WEISS *et al.*, 2000, p. 7). Nevertheless, there exist a number of inaccuracies in these calculations. The investigations in the study show that even in countries like Austria, with very detailed forest inventory data of a 5-year-period, estimates can rapidly reach a high level of uncertainty: *'these results have to be considered as hypothetical as they cannot be confirmed by measurements. Studies on this subject therefore seem to be indispensable.'* (WEISS *et al.*, 2000, p. 7). Doubts comprise the uncertainty of calculations for increments (the NFI does not provide data), uncertainties at the recalculation of C when applying conversion factors, and uncertainties of conversion factors themselves. Besides a comparison of forest area with the CORINE land cover data, the use of remote sensing for the NFI is not mentioned and can be assumed as being very limited (WEISS *et al.*, 2000, p. 34).

[6] The results of the recent national forest inventory (2000/2002) are available at http://bfw.ac.at/700/700.html (2004-10-04).

Having these circumstances in mind, the on-going Austrian project NEOS-QUICK clearly demonstrates the capabilities of remote sensing for the LULUCF sector. It examines the potential of remote sensing as a verification tool for LULUCF reporting and is based on a multi-sensor approach, integrating Geographic Information Systems (GIS) and ground observations. The project focuses on satellite imaging systems such as SPOT and Envisat ASAR, but also considers airborne systems (airborne imaging, airborne laserscanning) and medium-resolution satellite monitoring systems (Envisat MERIS)[7].

[7] For further information see http://www.geoville.com/neos/home.html (2004-08-31).

4 The Good Practice Guidance for Land Use, Land-Use Change and Forestry

4.1 Introduction

In the past, it has been recognised that the way humans use and manage their vegetation has a major impact on the amount of greenhouse gases being released to the atmosphere. Parties implementing their greenhouse gas inventories for both UNFCCC reporting and Kyoto Protocol reporting are obliged also to account for the greenhouse gases they emit (or store) through land use practices, which may contribute a significant proportion of national emission profiles (GREENHOUSE, 2004-08-06).

In order to achieve this reporting, the use of standard guidelines has a number of advantages, including the following (GREENHOUSE, 2004-08-06):

- Consistency: As all nations use the same reporting standards estimates of emissions and removals are easily comparable between countries.
- Accuracy: The good practices have been developed by experts from around the world guaranteeing that estimates of emissions from terrestrial ecosystems are accurate and uncertainty is minimised.
- Transparency: As all countries follow the same accounting guidelines, the emission inventories are comprehensible and transparent.

Following these advantages, the *GPG-LULUCF* can be regarded as a comprehensive set of instructions for the Parties, ranging from guidance on choice of methodologies, sampling design, estimation of greenhouse gas changes, reporting techniques, quality checks and supplementary specific recommendations (see IPCC, 2003).

4.2 History of origins

Already in 1998 the IPCC was invited to produce ‘good practice guidance’ to the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC Guidelines)*, in order to provide additional advice for the Parties establishing their inventories (see IPCC, 1997). This work was finished in the year 2000, when the IPCC published the *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (GPG-2000)* (see IPCC, 2000a). However, this work did not cover the land-use change and forestry sector because at that time also a *Special Report* on LULUCF was prepared (see IPCC, 2000b) and the IPCC wanted to prevent inconsistencies. As discussion on LULUCF carried more and more weight at UNFCCC negotiations, the IPCC recognised that it would be better to develop the *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. This single report completes the set of good practice guidance for all the sectors of the IPCC Guidelines (see IPCC, 2003).

The invitation of the UNFCCC to the IPCC is outlined in paragraph 3 of decision 11 at COP 7, the so-called ‘Marrakesh Accords’ (UNFCCC, 2002, pp. 54-55):

> The Conference of the Parties…
>
> 3. *Invites* the Intergovernmental Panel on Climate Change (IPCC):
>
> (a) To elaborate methods to estimate, measure, monitor, and report changes in carbon stocks and anthropogenic greenhouse gas emissions by sources and removals by sinks resulting from land use, land-use change and forestry activities under Article 3, paragraphs 3 and 4, and Articles 6 and 12 of the Kyoto Protocol, on the basis of the *Revised 1996 Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories*, taking into account the present decision (11/CP.7) and draft decision -/CMP.1 (*Land use, land-use change and forestry*) attached hereto, to be submitted for consideration and possible adoption to the Conference of the Parties at its ninth session;
> (b) To prepare a report on good practice guidance and uncertainty management relating to the measurement, estimation, assessment of uncertainties, monitoring and reporting of net carbon stock changes and anthropogenic greenhouse gas emissions by sources and removals by sinks in the land use, land-use change and forestry sector, taking into consideration the present decision (11/CP.7) and draft

> decision -/CMP.1 (*Land use, land-use change and forestry*) attached hereto, to be submitted for consideration and possible adoption to the Conference of the Parties at its ninth session;
>
> (c) To develop definitions for direct human-induced ‘degradation’ of forests and ‘devegetation’ of other vegetation types and methodological options to inventory and report on emissions resulting from these activities, to be submitted for consideration and possible adoption to the Conference of the Parties at its ninth session; and,
>
> (d) To develop practicable methodologies to factor out direct human-induced changes in carbon stocks and greenhouse gas emissions by sources and removals by sinks from changes in carbon stocks and greenhouse gas emissions by sources and removals by sinks due to indirect human-induced and natural effects (such as those from carbon dioxide fertilization and nitrogen deposition), and effects due to past practices in forests (pre-reference year), to be submitted to the Conference of the Parties at its tenth session.

At the 9th Conference of the Parties (COP 9), held in December 2003 in Milan, the Parties finally adopted the decision on *Good Practice Guidance for Land Use, Land-Use Change and Forestry* (IISD, 2004-08-06).

4.3 Structure of the Guidance

The *GPG-LULUCF* first gives a basic introduction and overview of the document as well as the historical background. Then it provides advice on different approaches to represent and classify land area depending on the character of available data (e.g. agricultural census data, forest inventory data, remote sensing data). The next part gives advice on the estimation of emissions of sources and the removals of sinks of CO_2 and non-CO_2 greenhouse gases. It is separated in six broad land-use categories, and aims at reducing the uncertainties as far as practicable, taking into consideration national circumstances. Estimates, however, are supposed to be *bona fide estimates* (IPCC, 2003, p. 1.6). The next chapter of *GPG-LULUCF* deals with information on specific requirements arising from the Kyoto Protocol, basically the identification of project boundaries, sampling strategies, and carbon pools. Furthermore, the *GPG-LULUCF* provides guidance on six cross-cutting topics, namely uncertainty assessment, sampling theories, identification of key categories, quality assurance and quality control, time series consistency, and verification.

4.4 General inventorying and reporting steps

The *GPG-LULUCF* provides a sequence of a general inventorying process for the Parties reporting to the UNFCCC and offers additional steps, which are relevant to those Parties that are reporting for the Kyoto Protocol.

The general steps for UNFCCC reporting can be outlined as follows (IPCC, 2003, p. 3.11):

- Definition of *land-use categories* and estimation of each land area,
- Implementation of *key category assessment* for the sectors LULUCF, greenhouse gases and carbon pools to find out the most important categories,
- Definition of the appropriate *tier* (Tier 1, 2, or 3) for the estimation procedure (according to availability of data),
- Collection of *activity data* (land area, management regime, lime and fertiliser use, etc.) and emission/removal factors appropriate for the selected tier,
- *Estimation* of emissions and removals of greenhouse gases,
- Performance of *uncertainty assessment* for each estimate,
- *Reporting emissions/removals* in a common reporting format using specific ‘reporting tables’,
- Implementation of *quality assurance and quality control* procedures, followed by an expert peer review.

The procedure of the Kyoto Protocol reporting follows mainly the already common UNFCCC reporting scheme, but the implementation has to be carried out in more detail. Supplementary methods arising from the Kyoto Protocol reporting comprise (IPCC, 2003, pp. 4.10-4.12):

- *Definition of parameters* (like the parameters forest area, forest crown closure and forest tree height),
- *Identification of land* subject to Article 3.3 (afforestation, reforestation, and deforestation) and elected activities under Article 3.4 (forest management, cropland management, grazing land management, or revegetation),
- *Estimation* of carbon stock changes and non-CO_2 greenhouse gas emissions for these lands, and also for projects under Article 6 and Article 12,

- *Reporting and documentation* of calculations and the uncertainties respectively.

The following sections of this thesis give a closer view on some of the major inventorying steps.

4.5 Representing land area through land-use categories

The first actual reference to remote sensing is given in the *GPG-LULUCF* at the passage where information about land area is needed to estimate the carbon stocks and the emissions and removals of greenhouse gases (IPCC, 2003, p. 2.6). The document presents six land-use categories, which are consistent with the IPCC Guidelines, *'reasonably mappable by remote sensing methods'* and furthermore complete, meaning that all land area within a country is included (IPCC, 2003, pp. 2.5-2.6).
The six land-use categories (also referred to as *'top-level categories'*) are as follows (IPCC, 2003, p. 2.6):

> **(i) Forest land**
> This category includes all land with woody vegetation consistent with thresholds used to define forest land in the national GHG inventory, sub-divided at the national level into managed and unmanaged, and also by ecosystem type as specified in the IPCC Guidelines. It also includes systems with vegetation that currently fall below, but are expected to exceed, the threshold of the forest land category.
>
> **(ii) Cropland**
> This category includes arable and tillage land, and agro-forestry systems where vegetation falls below the thresholds used for the forest land category, consistent with the selection of national definitions.
>
> **(iii) Grassland**
> This category includes rangelands and pasture land that is not considered as cropland. It also includes systems with vegetation that falls below the threshold used in the forest land category and are not expected to exceed, without human intervention, the threshold used in the forest land category. The category also includes all grassland from wild lands to recreational areas as well as agricultural and silvi-pastural systems, subdivided into managed and unmanaged consistent with national definitions.

(iv) Wetlands

This category includes land that is covered or saturated by water for all or part of the year (e.g. peatland) and that does not fall into the forest land, cropland, grassland or settlements categories. The category can be subdivided into managed and unmanaged according to national definitions. It includes reservoirs as a managed sub-division and natural rivers and lakes as unmanaged sub-divisions.

(v) Settlements

This category includes all developed land, including transportation infrastructure and human settlements of any size, unless they are already included under other categories. This should be consistent with the selection of national definitions.

(vi) Other land

This category includes bare soil, rock, ice, and all unmanaged land areas that do not fall into any of the other five categories. It allows the total of identified land areas to match the national area, where data are available.

In order to represent land areas three different approaches are introduced (IPCC, 2003, pp. 2.7-2.17), which are not to be seen as hierarchical steps, but are as steps increasing the level of information content. *Approach 1* uses basic land-use data such as forestry or agricultural statistics and identifies the total area for each individual land-use category. The final result is a table of land use at given points of time. *Approach 2* additionally establishes the changes from and to a category and changes between categories by taking into account different emission/removal factors for different land uses. It results in a non-spatially explicit land-use matrix where all the changes into and out of land categories can be tracked. *Approach 3* can be seen as an extension of Approach 2 by using spatial units such as grid cells or polygons sampled from remote sensing, ground surveys, interviews, or questionnaires usually recorded in a GIS. At this stage, land-use changes can even be tracked on a spatial basis and the final product is a spatially explicit land-use change matrix. When utilising this approach it is good practice to use ground reference data to avoid possible misclassification of land types and to describe mapping accuracy. Furthermore, decision trees for the identification of the suitable approaches are presented.

It is likely that most countries have some existing land-use data (e.g. forest databases, historic data, ground survey data, census data etc.) and are hence able to follow Approach 1 (IPCC, 2003, p. 2.14). If countries do not have access to remote sensing resources, they are unlikely to be able to follow the Approaches 2 or 3. Nevertheless, they should be able to use at least Approach 1 by means of FAO data (database on land use and land-cover) or other internationally available datasets. For this purpose, examples of approaches and of international land-cover data sets with technical specifications are presented in *GPG-LULUCF*, e.g. the USGS Global Land Cover Dataset or the CORINE land cover database (IPCC, 2003, pp. 2.23-2.28). The relationship between accessibility of data and the choice of the suitable approach is shown in Table 3.

Table 3: Relationship between accessibility of data and approaches to represent land areas through land area categories.

Accessibility to land area data	Remote sensing resources	Recommendation	Approach
- (N/A)	- (N/A)	Use of pre-defined land cover data sets	Approach 1
~ (limited)	+ (good)	Emphasis on RS	Combination of Approaches 2/3
+ (good)	~ (limited)	Emphasis on field survey	Combination of Approaches 2/3
+ (good)	+ (good)	Use of GIS and RS	Approach 3

4.6 Identification of key categories

The abovementioned term *key category* is defined in the glossary of the *GPG-LULUCF* as *'a category that is prioritised within the national inventory system because its estimate has a significant influence on a country's total inventory of direct greenhouse gases in terms of the absolute level of emissions, the trend in emissions, or both'* (IPCC, 2003, p. G.11).

The concept of key categories is to identify those categories of resources that contribute the greatest part to the overall inventory levels. By doing so the Parties can prioritise their efforts and improve their total estimates (IPCC, 2003, p. 5.29). A category or subcategory can be identified as key category if it accounts for 25-30% of the overall emissions or removals (IPCC, 2003, p. 5.31). The following Table 4 on the next page gives definitions of pools that may constitute a subcategory.

Table 4: Definitions for terrestrial pools (IPCC, 2003, p. 3.15).

Subcategory/Pool		Description
Living Biomass	Aboveground biomass	All living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. Note: In cases where forest understorey is a relatively small component of the aboveground biomass carbon pool, it is acceptable for the methodologies and associated data used in some tiers to exclude it, provided the tiers are used in a consistent manner throughout the inventory time series.
	Belowground biomass	All living biomass of live roots. Fine roots of less than (suggested) 2 mm diameter are often excluded because these often cannot be distinguished empirically from soil organic matter or litter.
Dead Organic Matter	Dead wood	Includes all non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil. Dead wood includes wood lying on the surface, dead roots, and stumps larger than or equal to 10 cm in diameter or any other diameter used by the country.
	Litter	Includes all non-living biomass with a diameter less than a minimum diameter chosen by the country (for example 10 cm), lying dead, in various states of decomposition above the mineral or organic soil. This includes the litter, fumic, and humic layers. Live fine roots (of less than the suggested diameter limit for belowground biomass) are included in litter where they cannot be distinguished from it empirically.
Soils	Soil organic matter	Includes organic carbon in mineral and organic soils (including peat) to a specified depth chosen by the country and applied consistently through the time series. Live fine roots (of less than the suggested diameter limit for belowground biomass) are included with soil organic matter where they cannot be distinguished from it empirically.
Note: National circumstances may necessitate slight modifications to the pool definitions used here. Where modified definitions are used, it is good practice to report upon them clearly, to ensure that modified definitions are used consistently over time, and to demonstrate that pools are neither omitted nor double counted.		

Decreases in one of these pools may be balanced by increases in another pool, thus changes in one single pool can be greater than those of all pools together (IPCC, 2003, p. 4.30).

4.7 Estimation of greenhouse gas emissions and removals

The *GPG-LULUCF* introduces three hierarchical Tiers of methods for the estimation of emissions and removals of CO_2 and non-CO_2 greenhouse gases based on the six broad land-use categories as already mentioned (IPCC, 2003, pp. 3.16-3.17). In general, these methods range from an uncertain approximation with default data to the design of advanced estimation-models where country-specific circumstances are being considered (IPCC, 2003, p. 3.17):

> The Tier 1 approach employs the basic method provided in the IPCC Guidelines (Workbook) and the *default emission factors* provided in the IPCC Guidelines (Workbook and Reference Manual) with updates in this chapter of the report. For some land uses and pools that were only mentioned in the IPCC Guidelines (i.e. the default was an assumed zero emissions or removals), updates are included in this report if new scientific information is available. Tier 1 methodologies usually use *activity data that are spatially coarse*, such as nationally or globally available estimates of deforestation rates, agricultural production statistics, and global land cover maps.
>
> Tier 2 can use the same methodological approach as Tier 1 but applies *emission factors* and activity data, which are defined, *by the country* for the most important land uses/activities. Tier 2 can also apply stock change methodologies based on country-specific data. Country-defined emission factors/activity data are more appropriate for the climatic regions and land use systems in that country. Higher resolution activity data are typically used in Tier 2 to correspond with country-defined coefficients for specific regions and specialised land-use categories.
>
> At Tier 3, higher order methods are used including models and inventory measurement systems tailored to address *national circumstances*, repeated over time, and driven by *high-resolution activity data* and disaggregated at sub-national to fine grid scales. These higher order methods provide estimates of greater certainty than lower Tiers and have a closer link between biomass and soil dynamics. Such systems may be *GIS-based* combinations of age, class/production data systems with connections to soil modules, integrating several types of monitoring. Pieces of land where a land-use change occurs can be tracked over time. In most cases, these systems have a *climate dependency*, and thus provide source estimates with interannual variability. Models should undergo *quality checks, audits, and validations.*
>
> (Accentuations were made by the author of this thesis.)

The glossary of the *GPG-LULUCF* provides the following definition for the term *activity data* (IPCC, 2003, p. G.2):

> Data on the magnitude of human activity resulting in emissions or removals taking place during a given period of time. In the LULUCF sector, data on land areas, management systems, lime and fertilizer use are examples of activity data.

For each Tier the *GPG-LULUCF* quotes carbon stock coefficients or ‘emission factors’ to achieve the source or sink estimates. The sections of *GPG-LULUCF* then follow this schedule by providing guidance for each land use, greenhouse gas and subcategory in all three Tiers. Utilised properly, the application of these Tier methods allows a step-by-step reduction of uncertainty and in return an increase of accuracy, which is one of the overall aims of *GPG-LULUCF*.

As can be seen in Figure 7, according to each Tier, the estimation procedure slightly varies, and the Parties are provided with decision trees for the correct identification of the appropriate Tier. The example shows a decision tree for the land-use category 'forest remaining forest land' (FF). In an iterative process, the appropriate Tier for each greenhouse gas and subcategory, namely living biomass, dead organic matter and soils, has to be determined.

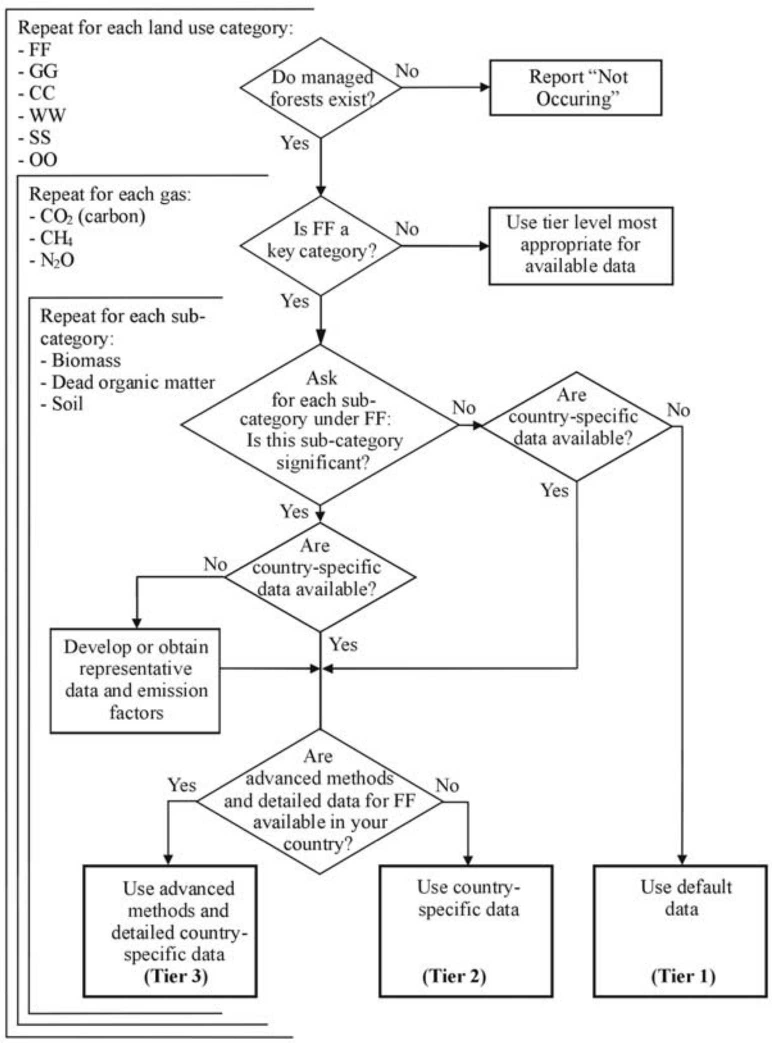


Figure 7: Decision tree for the identification of the appropriate Tier for the estimation process (IPCC, 2003, p. 3.18)

For the final reporting, consistent terminology has to be used: emissions are always denoted positive (+) and removals negative (–), and both are reported in gigagrams (Gg). These values have then to be reported using specific ‘reporting tables’ to maintain comparability.

4.8 Uncertainty assessment and remote sensing

Estimates in the sector LULUCF can have different levels of precision, accuracy and bias (IPCC, 2003, p. 3.68). These estimates are influenced by the availability and consistency of data in a country, as well as the used Tier level. Thus, the IPCC (2003, pp. 4.36-4.37) discriminates the following kinds of errors, which lead to uncertainties: sampling errors, definitional errors, classification errors, activity data errors, identification errors, model errors, and sampling errors.

Which factors actually dominate uncertainty and what is the range of uncertainty? With respect to remote sensing, the dominant errors are (a) inadequate image resolutions, (b) positional errors and (c) classification errors (IPCC, 2003, p. 4.37). For this purpose, the *GPG-LULUCF* references to a wide range of studies with the general purpose of minimising levels of uncertainties, concerning biomass expansion factors, parameter-retrieval, flux-measurements, calibrating of earth observation systems, and using country-specific data for verification. For example, LAITAT *et al.* (2000) have investigated 16 European forest inventories and showed that uncertainties in forest volume vary between 1-15%. Furthermore, they state that due to highly different procedures these national forest inventories lack comparability.

Even more ranges of uncertainty can be observed when it comes to estimates of carbon content in other land use categories such as cropland with Tier 1, where a *‘default uncertainty level of ±75% of the parameter value has been assigned based on expert judgement’*. The error ranges of rice paddies in temperate and tropical regimes even increase up to ±90% (IPCC, 2003, p. 3.73; p. 3.77). The uncertainty of activity data derived by remote sensing can be minimised in combination with ground-based surveys, leading to a range of ±10-15% (IPCC, 2003, p. 3.32).

4.9 Verification and remote sensing

The *GPG-2000* defines the term *verification* in its glossary as follows (IPCC, 2000a, p. A3.20):

> Verification refers to the collection of activities and procedures that can be followed during the planning and development, or after completion of an inventory that can help to establish its reliability for the intended applications of that inventory. Typically, methods external to the inventory are used to check the truth of the inventory, including comparisons with estimates made by other bodies or with emission and uptake measurements determined from atmospheric concentrations or concentration gradients of these gases.

The main purpose for the examination of verification processes is the increase in reliability and therefore the improvement of inventories (IPCC, 2003, p. 5.61). Moreover, verification builds confidence in estimates and helps to improve scientific understanding. Special attention to remote sensing is given in a chapter of *GPG-LULUCF* called ‘Verification Approaches’, stating that *‘remote sensing is the most suitable method for the verification of land areas’* (IPCC, 2003, p. 5.71).

Five different verification approaches are compared according to their applicability, as can be seen in Table 5 on the next page.

Table 5: Applicability of verification approaches for different requirements in the sector LULUCF (IPCC, 2003, p. 5.63).

	Approach 1 **Comparison with other inventories and other independent datasets**	**Approach 2** **Applying higher tier methods**	**Approach 3** **Direct measurement**	**Approach 4** **Remote sensing**	**Approach 5** **Modelling**
Land area	Suitable, if data are available	Suitable, if data are available	Not applicable	Suitable	Not applicable
Carbon pools					
Aboveground biomass	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Suitable (ground data needed)	Suitable (regression, ecosystem and growth models)
Belowground biomass	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Not applicable	Suitable (regression, ecosystem and growth models)
Dead wood	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Not applicable	Applicable (ecosystem and inventory-based models)
Litter	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Not applicable	Applicable (ecosystem and inventory-based models)
Soil organic matter	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Not applicable	Suitable (ecosystem and inventory-based models)
Non-CO_2 greenhouse gases	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Not applicable	Suitable (ecosystem models)
Emission factors	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Not applicable	Suitable (ecosystem models)
Activity/land-based report					
Forest, grassland, cropland, other land uses	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Suitable, particularly to identify land cover/land use and their changes	Suitable; Data-intensive; Can be an alternative approach when estimates from direct measurements and remote sensing are not available
Afforestation, Reforestation, Deforestation, projects	Suitable, if data are available	Suitable, if data are available	Suitable (resource-intensive)	Suitable, particularly to identify land cover/land use and their changes	Not practical

One can see that remote sensing (approach 4) holds strong potential for the verification of land-cover/land-use attribution as well as the detection of land-cover change. Remote sensing thus appears suitable for estimating aboveground biomass, but only if ground data is provided. Nevertheless, certain drawbacks come along, namely that remote sensing is not applicable for the verification of belowground biomass, litter, dead wood and soil organic matter. When using remote sensing as a tool to verify land use and land-use changes it has to be remarked that techniques are capable of detecting changes in *land-cover* (e.g. from forest to non-forest), but possibly inaccurate information on changes in *land use* (e.g. from crop A to crop B). The *GPG-LULUCF* in this case suggests a combination of frequent observation (with moderate spatial resolution platforms) assisted by detailed punctual observation (with high-resolution sensors). In order to verify changes in living biomass remote sensing has a great potential not only for the provision of vegetation indices (e.g. the Normalized Difference Vegetation Index, NDVI), but also for the use of correlation equations where biomass can be estimated using image data.

4.10 Sampling theory and sampling design

Sampling is the process of attaining information on an entire population by choosing single observations, where different statistical methods can be discerned (e.g. systematic sampling, random sampling, etc.). The *GPG-LULUCF* gives advice how to use auxiliary data for stratification (sampling of each subpopulation). These data may consist of administrative boundaries, boundaries of forest administrations, maps, or remote sensing data (IPCC, 2003, p. 5.22).

When talking about estimating changes, three common sampling designs can be outlined (IPCC, 2003, p. 5.23):

- The sampling units remain the same for both occasions (permanent sampling units);
- Independent sets of sampling units are used on both occasions (temporary sampling units);
- Some sampling units are substituted between occasions while others remain unmodified (sampling with partial replacement).

4.11 Supplementary methods arising from the Kyoto Protocol

The human-induced activities, which are determined in Art. 3.3 (afforestation, reforestation, deforestation) and 3.4 (forest management, cropland management, grazing land management or revegetation) have specific further implications on the inventorying process, for example definitional differences or specific requirements on the identification of land.

4.11.1 Definitional requirements for the Kyoto Protocol reporting

For explicit information on aforementioned terms, the reader is referred to the definitions in Chapter 2.6.

This section gives special attention to some examples of definitions, which have to be determined by each Party by the end[8] of 2006, i.e. for the parameter *forest* they must chose a minimum area (0.05-1 ha), minimum crown closure at maturity (10-30%), and a minimum tree height (2-5 m). After determining these parameters, the numerical values cannot be changed during the commitment period. The Parties may also use their own definitions, which should be consistent with the national land categorisation under UNFCCC reporting (IPCC, 2003, p. 4.11; p. 4.20).

Furthermore, the given definitions imply that (IPCC, 2003, p. 4.15):

- Forest management may only take place on lands that meet the definition of forest;
- Revegetation can only take place when the land is forest neither before nor after the transition (otherwise it would be afforestation, reforestation or forest management); and
- Grazing land and cropland management can take place on either forest or non-forest lands, but will be predominantly on non-forest lands in practice. Any forest land under grazing land or cropland management can be subject to a deforestation activity.

Additionally, the following arguments, among a set of other things, are determined (IPCC, 2003, p. 4.16):

[8] Parties have to specify country-specific parameters until 31st December 2006, or one year after entry into force of the Kyoto Protocol, whichever is later (IPCC, 2003, p. 4.28).

- The total land area[9] included in Articles 3.3 and 3.4 cannot decrease,
- Each area can only be reported under one single activity,
- Land cannot shift from one elected activity to another activity of Article 3.4.

The definition of forest can also be met by young forest stands, which currently do not meet the height or crown cover criteria, given that the trees reach these thresholds at maturity (IPCC, 2003, p. 4.52). In this case, *GPG-LULUCF* suggests distinguishing these areas from non-forest areas on 31st December 1989, for as they do not meet the requirements for afforestation or reforestation.

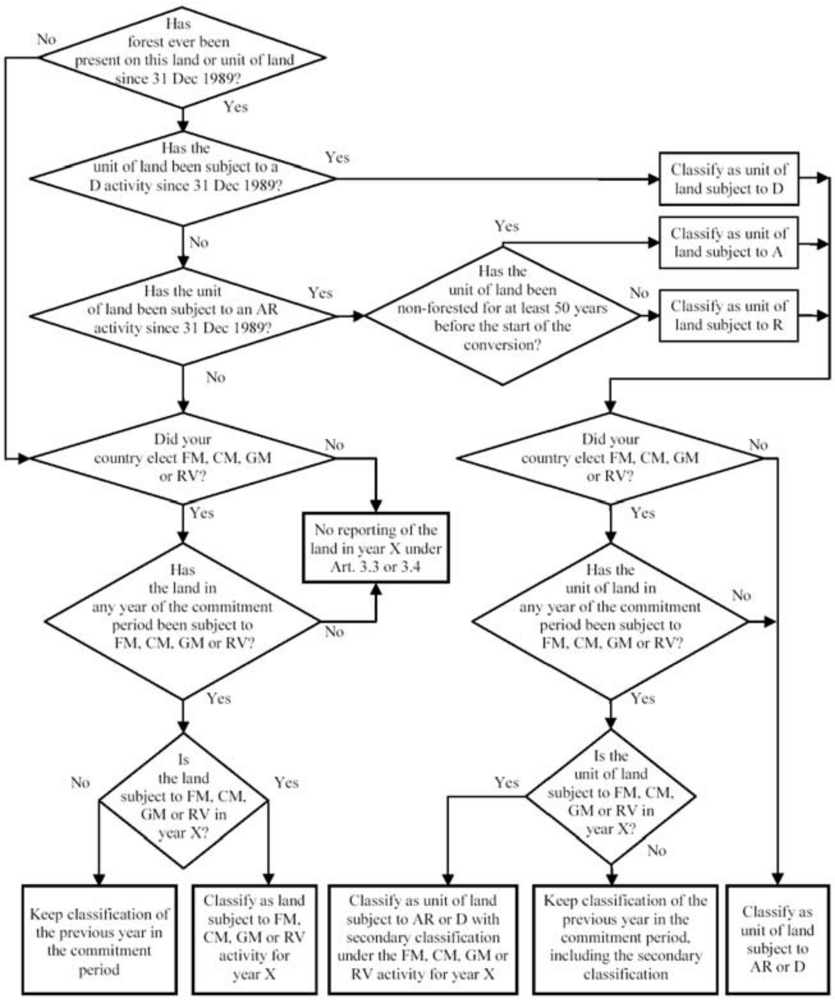
4.11.2 Identification of land

Figure 8 on the next page gives an example of a decision tree that helps the Parties to distinguish between Article 3.3 and Article 3.4 activities and identifies how to classify land at any given point of time within the commitment period (IPCC, 2003, p. 4.14). This inquiry can be made iteratively for each year of the commitment period, in order to prevent misclassification or double counting.

If a country has elected, for instance 0.5 ha as the minimum area for forest, the Party must also identify any deforestation events that are 0.5 ha or larger. *GPG-LULUCF* furthermore gives the advice to mind the shape of the polygons just as well, and therefore to define minimum widths of strips, which are 0.5 ha of land (IPCC, 2003, p. 4.27).

[9] The *GPG-LULUCF* is following the terminology of the Marrakesh Accords: the term *units of land* refers to areas which are defined under Article 3.3 (afforestation, reforestation, and deforestation), and *land* refers to areas which are defined under Article 3.4 (forest management, cropland management, grazing land management, or revegetation) (IPCC, 2003, p. 4.10).

Figure 8: Decision tree for classifying a unit of land under Article 3.3 or Article 3.4 (IPCC, 2003, p. 4.14).



4.11.3 Reporting and documentation process

Based on what has just been said, the Kyoto Protocol reporting is more stringent and extensive. Additionally to the carbon estimates, the reporting comprehends the associated uncertainties for each carbon pool, greenhouse gas and geographical location. Thus, methodologies have to be described and changes in data have to be reported (IPCC, 2003, pp. 4.39-4.42).

For documentation, the Parties are to provide information on calculation of estimates, frequency of data collection, the choice of tiers, identification of geographical boundaries, the area in each productivity class and species, and the underlying scientific references (IPCC, 2003, p. 4.38; 4.51).

5 Discussion

The *GPG-LULUCF* gives a good overview of main principles and procedures of all major inventorying topics concerning the wide range of definition of estimation and quality control to reporting processes. The *GPG-LULUCF* repeatedly points out the significance of remote sensing to help the Parties to fulfil their inventory requirements, but further information on the precise application of remote sensing technologies is still desirable.

Few incentives for the use of remote sensing are given

The standards shown in the *GPG-LULUCF* give rise to concern, as they do not give specific incentives to improve reporting techniques if individual countries are not motivated to do so.

If results of independent studies differ greatly from official national reports, national authorities still have the excuse that *'emission estimates, even if uncertain, are bona fide estimates'*. In addition, improvements in data collection and methodological aspects can be deferred by arguing that the new methods are too costly and hence *'not practicable given national circumstances'* (IPCC, 2003, p. 1.3).

It is obvious that the Parties do have their own national inventorying mechanisms with well-defined directives, but, as can be seen in several chapters of the *GPG-LULUCF*, the methodologies are described in a very general manner.

Advice on judgement is missing in the *GPG-LULUCF*

One chapter of the *GPG-LULUCF* gives advice on representing land area. For calculation purposes, land area is the most important parameter as carbon stocks and emissions are calculated by multiplying the area with the corresponding biomass factors of the plant species or land use. The *GPG-LULUCF* quotes three approaches to describe land area, which should in general be adequate, consistent, complete and transparent (IPCC, 2003, p. 2.5). Nevertheless, the *GPG-LULUCF* neglects to give advice on the level of judgement. It seems that the Parties have to decide on their own which approach is the most adequate for their specific situation, an assumption that is rather unlikely.

Comparability of inventories is not guaranteed

The *GPG-LULUCF* states that the mentioned land area categories are consistent with the articles 3.3 and 3.4 of the Kyoto Protocol, and are broad enough to classify all land areas in most of the countries (IPCC, 2003, p. 2.5). The different definitions of categories could in fact cause difficulties in comparing the inventories of different countries. As already mentioned in the comparative study of LAITAT *et al.* (2000), this is a difficult task in European countries, and hence remote sensing serves as an independent tool to achieve a higher level of international harmonisation.

***GPG-LULUCF* as an example of IPCC's general guideline**

In the case of land area categories mentioned above, the IPCC is following its general guideline: at first, default parameters for application are supplied. If the Parties then are able to define an improved modus operandi, they are encouraged to implement improved steps, with the condition of reporting all work steps in detail and applying them consistently. This formula can be regarded as one example of IPCC's course of action, keeping in mind that documents to the extent of *GPG-LULUCF* are a labour-intensive output and can be assumed as a common denominator of all countries' national circumstances (SCHLAMADINGER, 2004). This is the reason why *GPG-LULUCF* gives no specific recommendation for the use of remote sensing.

Difficulties with the detection of land use change

Remote sensing turns out to be a valuable tool for the detection of *land-cover* change. As discussed previously, it might be difficult to distinguish between changes in *land use*, for example, when land use changes but land-cover remains the same. This is the case when it comes to tell the difference between a clear-cut of forest as part of forest management and a deforestation process. In this case, the *GPG-LULUCF* suggests the following three approaches (IPCC, 2003, p. 4.58):

(a) Reassessing of the units of land in certain time intervals (e.g. annual basis) to confirm whether regeneration happened, and then reclassifying to the correct land use.

(b) Following consistently the method that units of land, which have not been confirmed as being afforested/reforested, remain classified as non-forested land.

(c) Calculating the proportion of land area without forest cover on average statistical data, which is not expected to regenerate to forest, and then assigning this proportion to lands subject to deforestation.

Considerable efforts in monitoring land use have been made within the ongoing EU programme 'Control with Remote Sensing' (CwRS), where on a legal basis a uniform reporting and controlling scheme for the detection of fraudulent cases of land use was established, as described in WAGNER *et al.* (2002, p. 3). The approaches of this programme mainly consist in a combination of remote sensing and GIS for the identification of crop or cover type. In their paper, WAGNER *et al.* also investigate potential parallels between the CwRS and LULUCF activities, concluding that the strengths of remote sensing lie in objectivity and consistency, making it a suitable technique for verification and control activities across borders.

Austria does currently not use CwRS, because approx. 85% of the farmers get area-based aids in the context of several environmental measures. Together with the establishment of a 'Land Parcel Identification System' and a mountain cadastre, the control of eligibility has to be done via direct field visits anyway, disregarding the use of remote sensing (KIDD, 2004).

Impact of remote sensing is limited so far

Remote sensing can be regarded as a valuable tool in conjunction with already established techniques of inventories.

However, the relevance of remote sensing in official documents like the *GPG-LULUCF* is limited, due to still lacking quality standards, as well as problems with affordability and availability of data. Therefore, the IPCC cannot dictate the usage of such a particular method like remote sensing, but can only recommend it.

Remote sensing cannot provide target quantities directly

The direct derivation of carbon or biomass quantities through means of remote sensing is currently not feasible. Figure 9 shows three broad classes of remote sensing systems discerned by their geo-spatial characteristics. While airborne systems usually provide images with a very high resolution (a few cm), their costs are reasonably high and therefore operations are flown in an interval of several years to decades. On the other hand, monitoring systems provide frequent observations in an operational manner, but the images show very poor resolution (as coarse as several km). Satellite imaging systems can be ranked in between.

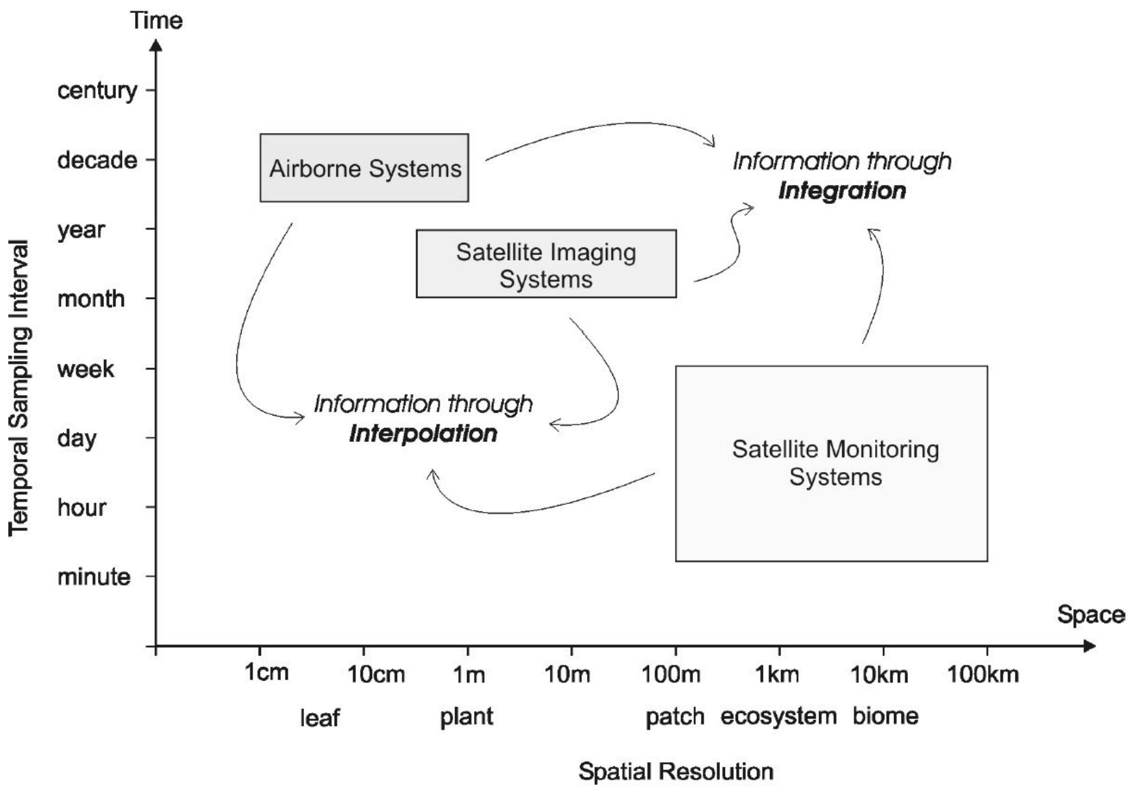


Figure 9: Remote sensing systems and scales of measurements (WAGNER and JONAS, 2003, p. 43).

As can be seen in Figure 9, the physical constraints of sensor characteristics can only be overcome by performing interpolation or integration of information. Remote sensing therefore cannot provide information directly, but needs highly specialised operational methods to valorise information content.

Smallest detectable unit of remote sensing

In accordance with the Marrakesh Accords, countries have to define several parameters like 'forest', as already described in previous chapters. Countries may also define an other threshold than 0.05 ha, so how could they detect units of land by remote sensing? Sensors, which will come into question for reporting land areas of 0.05 ha, therefore need to have a spatial resolution of at least 20-25 m. A review of actual sensors and systems, which will be available in the near future, shows that spectral resolution as well as spatial resolution increase dramatically, reaching 2.5 m with QuickBird and 220 bands with Hyperion (KRESSLER, 2003, p. 11), showing also great potential of future sensors and missions.

Remote sensing as economic contribution

Flexible schemes like the Kyoto Mechanisms are intended to support countries in reducing their emissions by trading with emission reduction units. Countries like the Russian Federation are likely to benefit substantially from this system, while still controversial arguments are being left. Especially the role of developing countries is still underestimated, as those countries are likely to increase their fossil fuel combustion parallel to economic growth (GRACE, 2004, p. 197). This paper furthermore gives advice on how to implement the Kyoto Mechanisms on a more ecological basis and recommends the use of remote sensing and GIS as one example of the linkage of the Kyoto Mechanism projects to '*technology transfer, training and capacity building*' (GRACE, 2004, p. 199).

Thus, it can be said that the economic impact of remote sensing in terms of satellite surveillance, land-use verification, and treaty compliance cannot yet be quantified.

International joint efforts are essential

The global impact of climate change needs sound answers of remote sensing research. This claim is, for example, addressed in ROSENQVIST *et al.* (2003a, p. 451) where '*it is recommended that a considerable part of international remote sensing research activities be focused and aligned to fulfil the specific information needs posed by the Kyoto Protocol*'. A study about the use of remote sensing supporting 'multilateral environment agreements' (MEAs) observes that remote sensing contributes valuable data over different time and scale frames and valorises national-level data, '*which are often under-resourced and inconsistent from country to country*' (DE SHERBININ, 2001, p. 7). Furthermore, the authors recommend the development of long-term data continuity, especially the steadiness of the Landsat programme, and suggest a price cut for remotely sensed data to support multilateral environment agreements (DE SHERBININ, 2001, pp. 7-8). In addition, referring to the 'American Institute of Aeronautics and Astronautics' (AIAA), the study of PETER (2004, p.

482) shows that remote sensing can support multilateral environment agreements *'from the identification of a new environmental problem (pre-negotiation phase) to the monitoring (negotiation phase) and assessment (implementation phase) of that problem, to the verification of compliance and subsequent enforcement (compliance and dispute resolution)'*. These promising tasks may only be undertaken by using strong international efforts.

5.1 Future trends in remote sensing

In the year 2000, when IPCC published its *Special Report on Land Use, Land-Use Change and Forestry* it is stated that *'there is no published national or international commitment to ensure that remote-sensing measurements adequate to determine areas of forest clearing and regrowth will be collected during the first commitment period'* (IPCC, 2000b, p. 103). Besides, the report points out the long period of image acquisition in some regions, where data are often taken several years apart and may not coincide with the desired (annual or 5-year) time frame (IPCC, 2000b, p. 349). Therefore, the *GPG-LULUCF* gives advice on the implementation of an operational earth observing system for the first commitment period (IPCC, 2000b, p. 104).

According to the LULUCF sector, the IPCC surveys data needs and methods for implementing Article 3.3 and comes to the conclusion that the potential of remote sensing for reporting and detecting activities of afforestation, reforestation, and deforestation is reasonably low, as can be seen in Table 6 (IPCC, 2000b, pp. 154-155).

Table 6: Data needs and methods for implementing Article 3.3 (IPCC, 2000b, p. 153).

Data Requirement	Remote sensing	Forest inventory	Activity reporting
1990 forest extent	✓	✓[a]	
2012 forest extent	✓	✓[b]	
A/R activities undertaken			✓[c]
D activities undertaken	✓		✓[d]
1990 carbon stock		✓[b]	
2008 carbon stock		✓[b]	
2012 carbon stock		✓[b]	
C stock before deforestation		✓[b]	
C stock at beginning of activity that starts after 2008		✓[b]	✓
For forest extent			
Land use		✓	✓
Percent cover	✓	✓	
Regeneration potential		✓	✓[e]
Carbon density		✓	
Cover class	✓	✓	

[a] Where forest is present in inventories subsequent to 1990, it should be possible to determine if that forest originated since 1990. In some cases, this will represent AR activities. Where forest is not present in inventories after 1990, it may be impossible to determine from sample plots whether forest was present in 1990.
[b] If inventory dates do not match specific years of interest, models can be used to project inventory conditions to the beginning and end year of commitment periods.
[c] It is assumed that activities beneficial to a country would be reliably reported in an activity reporting mechanism.
[d] Identification of deforestation through activity reporting relies heavily on enforcement of permitting or reporting regulations. Verifiability could be difficult to ensure.
[e] Some sustainable forestry verification methods require reporting of adequate regeneration.

Although since the publication of the abovementioned report in 2002 major efforts in research have been made and new satellite systems like Envisat[10] have been launched, this subject still

[10] The launch of Envisat took place on March 1, 2002. See http://envisat.esa.int/m-s/ (Mission and system) for further details (2004-10-19).

remains current. This raises the following questions: What is remote sensing capable to achieve? What are the future trends in remote sensing?

BONN (2004, p. 6) outlines some tendencies in the fields of data supply, where novel data suppliers like India and China come along, as well as the evolution of the user community, meaning that an increasing number of user communities is using a wider spectrum of data and sophisticated applications. He points out to so far well-established international co-operations like the GMES programme and the 'International Charter on Space and Major Disasters' for coordinating remote sensing resources in times of disasters. He calls for narrowing the widening technology gap between rich and poor regions, which appear also as a gap in the accession to knowledge. One concluding suggestion remains viable, namely the use of a data clearinghouse serving as a single-access-point for all the geo-spatial information about a given location or sector.

The paper also gives a list of unanswered questions concerning the violability of our environment. Some of them can be regarded as research topics for near future (BONN, 2004, p. 4, modified):

- *Biosphere including soils covers less than half of the continents and is very thin. Can satellites help to forecast its evolution?*
- *Tropical forests continue to be cut or burnt. Can satellites give us the right figure?*
- *How long can we continue to boost agriculture and lose soils by erosion or salinisation? Can satellites help us to model these changes?*
- *Water quality is affected by human-induced land use changes in catchments. Can it be improved?*
- *Will the level of atmospheric CO_2 continue to rise? Where does all this carbon go?*
- *What is the amount of C stored in biomass, soils, and oceans? Does it change?*
- *Can natural and technological hazards be managed with the help of space data? Not only monitored, but also prevented?*
- *Can the people in charge of environment and security make an effective use of space data? Can this use go down to local and regional scales?*
- *Are the governments coherent in their local decisions regarding the Kyoto Protocol (e.g. transportation policies)?*
- *Can earth observation from space measure biodiversity and landscape quality?*

According to the sector LULUCF and the Kyoto Protocol, BÉGNI *et al.* (2002, p. 12) comment that *‘only a combination of data from remote sensing-based systems, forest inventory data collected in the field, experimental data from sample plots, and detailed socio-economic data on management practices and technological factors will meet the information requirements regarding land use and land cover changes in the post-Kyoto period’*. Furthermore, they compare existing systems with actual requirements and therefore define some missing elements and future requirements for Earth Observation (BÉGNI *et al.*, 2002, pp. 18-19):

- a better co-ordination of global scale activities that address the carbon observation either on European or international scales,
- a long-term continuity of earth observation data and stability of programmes,
- establishment of *in situ* belowground biomass measurements,
- maintenance of flux measurement networks and establishment of new stations in underrepresented areas (especially Asia and Africa),
- a scientific consensus about the relevance and performance of meso-scale models, with appropriate data and relevant accuracy.

6 Summary and conclusion

The present thesis looks at the question whether remote sensing plays a role in the *Good Practice Guidance for Land Use, Land-Use Change and Forestry (GPG-LULUCF)*. In order to evaluate this fact, the author first takes a look at international research in the framework of remote sensing and the Kyoto Protocol, and then discusses and compares how remote sensing is taken into consideration in the *GPG-LULUCF*.

Firstly, it can be said that very few studies concern explicitly look into the advantages of remote sensing. As can be seen in Chapter 3.2, most of the studies stress specific sensors like Landsat TM and SPOT because they were operational in the year 1990 and therefore can be used to generate the 1990 Kyoto baseline. Moreover, lively scientific discussion on the sink/source question is held, due to the still pertaining variability of data and uncertainties in the estimation of carbon pools. DONG *et al.* (2003, p. 408), for example, show differences up to 50% for total biomass between remotely sensed estimates and forest inventory estimates, which according to them occur due to residual atmospheric effects and unequal forest inventory estimates.

A matter of particular interest to the author is the situation in Austria. One of the few assessments of the situation of carbon accounting in Austria is the study of WEISS *et al.* (2000). The authors come to the conclusion that Carbon stocks represent about 40 times the Austrian CO_2 equivalents of greenhouse gas emissions. This fact underlines the importance of Austrian forests acting as carbon sinks. Nevertheless, this study refers to a number of inaccuracies (WEISS *et al.*, 2000, p. 7), which could be overcome by further research in remote sensing.

The *GPG-LULUCF*, a quite extensive work, refers to the significance of remote sensing in many different ways. It is not only an official document of the IPCC to help the Parties fulfil their inventory requirements, but can also be regarded as the ‘least common denominator’ of developed as well as developing countries’ circumstances in order to mitigate greenhouse gases and global warming (SCHLAMADINGER, 2004). As shown in Chapter 4 the *GPG-LULUCF* is laid out to help the Parties from around the world to estimate their greenhouse gas changes, report their emissions to the UNFCCC, as well as perform quality checks, and validate their estimates. As one procedure with great potential, the Guidance introduces the field of remote sensing and gives examples of how remote sensing can contribute to reach the targets required by the Kyoto Protocol. Referring to Chapter 4.9 remote sensing holds strong potential for the verification of land-cover/land-use attribution as well as the detection of land-cover change. Remote sensing thus appears suitable for estimating aboveground biomass, but only if ground data is provided. According to *GPG-LULUCF*, problems arise when it comes to the detection of belowground biomass, litter, dead wood, or soil organic matter. In this case, remote sensing is not regarded as being suitable.

The discussion shows some drawbacks arising with *GPG-LULUCF*. For example, the Guidance does not give specific incentives to improve the Parties' reporting techniques if they are not motivated to do so. One of the major problems to be solved is the comparability of inventories. Countries have a certain freedom to choose definitions for their national land use categories. This could lead to difficulties in comparing the inventories of the different countries.

The author comes to the conclusion that it is still left up to the remote sensing community to demonstrate the usefulness of remote sensing for verifying changes in living biomass and to improve existing terrestrial carbon cycle models, together with the integration of ground truth data.

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