Assessing the Status of the Development of Standards for the Essential Climate Variables in the Terrestrial Domain

Progress Report to the 26th Meeting of the Subsidiary Body for Scientific and Technological Advice (SBSTA)

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1. Introduction

In its Implementation Plan (GCOS, 2004) the Global Climate Observing System (GCOS) stated: "Many organizations make terrestrial observations, for a wide range of purposes. The same variable may be measured by different organizations using different measurement protocols. The resulting lack of homogeneous observations hinders many terrestrial applications and limits the scientific capacity to monitor the changes relevant to climate and to determine causes of land-surface changes." In response, the Conference of Parties in its ninth session (Decision 11/CP.9; UNFCCC, 2003):

> *"8. Invites the sponsoring agencies of the Global Climate Observing System, and in particular those of the Global Terrestrial Observing System, in consultation with other international or intergovernmental agencies, as appropriate, to develop a framework for the preparation of guidance materials, standards and reporting guidelines for terrestrial observing systems for climate, and associated data and products, taking into consideration possible models, such as those of the World Meteorological Organization/Intergovernmental Oceanographic Commission Joint Commission for Oceanographic and Marine Meteorology, and to submit a progress report on this issue to the Conference of the Parties at its eleventh session".*

Through the Global Terrestrial Observing System (GTOS), the Food and Agriculture Organization of the United Nations (FAO) commissioned a report in 2005 on the subject of establishing a framework for terrestrial climate-related observations (hereafter abbreviated as TCF). A progress report summarizing the above report was submitted to SBSTA/COP for its 23rd Session in Montreal, November 2005. In its response (UNFCCC, 2006, p. 16):

> *"The SBSTA welcomed the efforts by the GTOS secretariat to develop a framework for the preparation of guidance materials, standards and reporting guidelines for terrestrial observing systems for climate and encouraged the GTOS to continue its work. It also called on the GTOS secretariat* ***to assess the status of the development of standards for each of the essential climate variables in the terrestrial domain.*** *The SBSTA invited the GTOS secretariat to report on its progress by SBSTA 26 (May 2007)."*

The present document reports on the progress in the assessment of the status of the development of standards achieved by February 2007, as well as plans for completing this task prior to December 2007 - in time for SBSTA 27 at which issues regarding systematic observations will be discussed. This approach reflects communication from the SBSTA Secretariat (26 February 2007) which requested a report on progress for SBSTA 26, and a final report for SBSTA 27.

The approach employed and progress made are described in section 2., findings to date are summarized in section 3., plans for the next steps in section 4., and conclusions based on the work to date in section 5. Examples of documentation completed for individual essential climatic variables (ECV) are provided in the Annex.

2. Progress to date

The GCOS Implementation Plan (GCOS, 2004) identified 13 ECVs: Albedo, Biomass, Fire disturbance, Fraction of absorbed photosynthetically active radiation (FAPAR), Glaciers and ice caps, Ground water, Lake levels, Land cover (including vegetation type), Leaf area index, Permafrost and seasonally-frozen ground, River discharge, Snow cover, and Water use.

The question of standards for the terrestrial ECVs encompasses a very broad spectrum in terms of: (i) the environmental variables involved; (ii) the geographic coverage and diversity of these variables leading to different measurement approaches; (iii) the types of documents or formats relevant to the development of standards (standards, guides, protocols, guidelines); (iv) the areas in principle requiring standardization (initial measurements, data processing, analysis, final product); (v) the need for *in situ* as well as satellite measurements in most cases, requiring conceptually different approaches; (vi) the number and dispersal of sources where information relevant to standardization may be generated or archived (national monitoring agencies, national or international research programmes, international scientific programmes, intergovernmental or international organizations, organizations focusing on standardization of measurements, world data centers), and others. To make the task manageable and to respond to the SBSTA request as effectively as possible, the following approach was adopted for each ECV:

1. Identify potential sources of information. Depending on the case, these included searches of the lists of publications by
    - FAO, UNEP, UNESCO, WMO and IGBP;
    - International or important national data centers (e.g. WDCs, GOSIC, GRDC, etc.);
    - Large agencies producing or archiving terrestrial data sets (e.g. NASA, USGS);
    - Large research programmes with information available on the web (e.g. DAACs);
    - The scientific community - international scientific panels (e.g. CEOS and GTOS), international projects (e.g. GOFC-GOLD), and other international organizations or research programmes.
2. Identify documents that might be relevant to the development of standards for the terrestrial ECVs. This includes documents describing standards, guidelines, measurement or processing protocols, or guides that address the terrestrial ECVs directly or indirectly (e.g. documents that might contain relevant information, e.g. WMO guides dealing with hydrological measurements).
3. Obtain these documents where available (the majority through the Internet), review and extract relevant information.
4. Compile this information in a consistent format, adding conclusions and recommendations based on the reviewed materials.

The format for this report was developed to produce a document complementary to others already produced by the GCOS (GCOS, 2004, 2006). The focus was thus placed on the standards and similar information for the individual ECVs, not on the overall need for, and uses of, the information thus produced.

So far, initial versions of the documents have been produced for 10 among the 13 variables (all except Fire disturbance, Ground water, and Water use). The general findings are discussed in the next section. The plan for next steps is described in section 4. Examples of the completed reviews are attached in Annex 7.1-7.3.

3. Results to date

Initial reports have been prepared for 10 among the 13 terrestrial ECVs; examples are provided in the Annex. This section briefly discussed overall findings and impressions obtained so far, thus providing the rationale for the next steps. In this report, an ECV standard is assumed to be a document describing one specific approach to obtaining information on an ECV that has been broadly endorsed by the international community representing producers and users of such information.

a) Existence of standards

Overall, few standards appear to exist for the terrestrial ECVs. No internationally accepted standards that directly address the GCOS needs have been identified so far. On the other hand, there are guides for measurement methods which may describe several methods and discuss the utility of each, and measurement protocols that describe in detail how a specific terrestrial variable should be sampled and measured *in situ*.

The apparent absence of standards can be understood by considering the nature of terrestrial ECVs. *In situ* measurement approaches have been initially developed by individual agencies or research groups, and this development was affected by the available equipment (often produced in that country), tradition, available expertise, etc. with no need for international coordination or standardization. As a result, the existing procedures exhibit considerable diversity in techniques and approaches. This is true even for such well-established variables as precipitation measurements, as the work of WMO technical commissions shows. WMO approaches this problem by a) issuing "guides" which describe various procedures, their strengths and weaknesses, and applicability (e.g. WMO, 2006), and b) by supporting intercomparisons, calibration tests, and other initiatives which enable joint use of measurements by various methods (e.g. WMO, 1998).

Regarding satellite measurements, the complexity arises from differences among satellite sensors, their variable suitability to provide exactly the measurements needed, the limited spatial coverage (not all sensors provide full global coverage for an ECV), and the finite duration of individual satellite missions. To create ECV data sets required by the GCOS, comparability and consistency among products from different sensors/missions arise as key issues. This is the case when multiple products are generated or when sequential missions are launched. So the validation (for each generated product) and intercomparisons (among similar products) are the main issues. These are currently addressed by research teams, who as a matter of routine develop common protocols among themselves to be followed. Because of the diversity in input satellite data, it is not feasible (or desirable) to have one set of algorithms, although eventually the R&D can be expected to converge on the best methods and input data sources for ongoing applications. Nevertheless, the continuing technological evolution and the nature of satellite-based earth observation suggest that standardization in the above defined sense is not an appropriate approach. This is also reflected in the GCOS climate monitoring principles (GCOS, 2004) which include a suitable period of overlap between new and old satellite systems, and peer-review of new products. Such activities have indeed been taking place, e.g. intercomparisons among various LAI products by the CEOS Working Group on Calibration and Validation (http://lpvs.gsfc.nasa.gov/).

b) Other document types

In general, guides, measurement protocols, and guidelines are other means for encouraging and enabling acquisition of terrestrial observations that may lead to consistent products (in time and space) for use in climate monitoring. These have been used to various degrees for terrestrial ECVs and are established to a greater or lesser degree, depending on the ECV. The *in situ* approaches are well documented for some variables in various countries, and such information is available on the Internet. Depending on the ECV, few (e.g. Permafrost and seasonally-frozen ground) or many (Land cover) such documents may exist. In some cases, they obviously must exist but are difficult to access (e.g. Biomass).

In case of ECVs relying primarily on satellite measurements, the methods are evolving and often vary among programmes or satellite missions. However, the progress towards common or comparable methodologies and products has been accelerating through various projects and CEOS-supported initiatives, especially for Albedo, Fraction of absorbed photosynthetically active radiation (FAPAR), Leaf area index, Fire disturbance, and Land cover (Snow cover products are fairly mature (IGOS, 2006) and relatively few at the global level). These efforts have so far resulted in best practice guidelines (e.g. for Land cover), in documents describing various measurement procedures and their proper use (e.g. for Leaf area index), and in the convergence of approaches to the generation of global products (e.g. Fire disturbance). So far, in most cases these procedures represent the view of a scientific community (or its subset) and do not have a "formal" stamp of approval.

4. Next Steps

Subject to comments and feedback by the SBSTA, GTOS plans to:

- Complete the review of the remaining ECVs (Fire disturbance, Ground water, Water use).
- Enhance the reviews for all ECVs by collecting additional materials, where feasible.
- Obtain peer review and comments on the resulting documents.
- Submit the results to the SBSTA 27 meeting.

5. Recommendations

It is recommended that the SBSTA:

1. Comment on the adequacy of the approach taken so far and the proposed next steps, and identify desirable improvements.
2. Request completion of the work and its submission to the SBSTA 27.

6. References

GCOS. 2004. Implementation plan for the Global Observing System for Climate in Support of the UNFCC. Report GCOS – 92 (WMO/TD No. 1219). 136p. + Appendices.

GCOS. 2006. Systematic observation requirements for satellite-based products for climate. Supplemental details to the satellite- based component of the "Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC", Report GCOS-107 (WMO/TD No. 1338), Geneva, Switzerland. 90p.

IGOS. 2006. IGOS Cryosphere Theme For the Monitoring of our Environment from Space and from Earth. Report Version 0.9.5.1. 118p.

WMO. 2006. Guide to meteorological instruments and methods of observation. Report WMO-No. 8, Preliminary seventh edition, World Meteorological Organization, Geneva, Switzerland.

WMO. 1998. WMO Solid Precipitation Measurement Intercomparison: Final Report, (B. E. Goodison, et al.), Instruments and Observing Methods Report No. 67, WMO/TD-No. 872, Geneva, Switzerland.

7. Annex

This Annex contains three examples of the reviews prepared for 10 among the 13 ECVs. The examples represent variable relying primarily on satellite observations (Leaf area index); primarily on *in situ* observations (biomass); and on a combination of the two (Glaciers), respectively.

Please note that these reviews are still undergoing modification as comments are received from stakeholders.

7.1 Leaf Area Index

Leaf Area Index (LAI) measures the amount of leaf material in an ecosystem, which imposes important controls on photosynthesis, respiration, rain interception, and other processes that link vegetation to climate. Consequently, LAI appears as a key variable in many models describing vegetation-atmosphere interactions, particularly with respect to the carbon and water cycles (GCOS, 2004). The interest in information on LAI distribution and changes has grown substantially in recent decades, due to its intrinsic importance and the emerging capability for LAI estimation over large areas using satellite measurements.

1. Definitions and units

LAI was first defined in 1947 as the total one-sided area of photosynthetic tissue per unit ground surface area. After reviewing various other definitions (some measurement approach – dependent), Jonckheere *et al.* (2004) concluded that in current literature, LAI is defined as one half of the total leaf area per unit ground surface area. They also noted that different definitions can result in significant differences between calculated LAI values. LAI is a dimensionless quantity (or m^2/m^2).

2. Existing *in situ* measurement methods and standards

Direct and indirect *in situ* LAI measurement methods have been developed. The various methods were described and discussed in two recent reviews (Jonckheere *et al.*, 2004; Breda, 2003).

2.1 Direct methods

Direct methods are accurate but labour intensive and therefore used in a limited way. They consist of two steps, leaf collection and leaf area measurement.

<u>Leaf collection:</u>

a) Harvesting methods:

- Destructive sampling: collection and removal of green leaves from a sampling plot.
- “Model tree” method: destructive sampling of a small amount of representative trees out of the stand, from which the leaf area and vertical distribution of leaf area is measured leaf by leaf.
- Non-harvesting litter traps (in deciduous forest, see also below): collection during autumn leaf-fall period.

b) Non-harvest methods:

- Leaf litter collection during the leaf-fall period employs “traps” (open boxes with predetermined size and lateral sides that prevent wind blowing leaves into or out of the traps). There seems to be no consensus on the sampling design of the traps (Jonckheere *et al.*, 2004). Litter traps assume that the leaves captured represent the whole stand. They provide an integrated measure for LAI, but neither an accurate measure at a specific time during the growing season nor a vertical LAI profile; climate can also have an effect on the data from litter traps (Jonckheere *et al.*, 2004 and references therein).

Leaf area determination:
Leaf area can be calculated by means of either planimetric or gravimetric techniques.

- Planimetric approach: based on the correlation between the individual leaf area and the number of area units covered by that leaf in a horizontal plane (Jonckheere *et al.*, 2004). Leaf perimeter can be measured with a planimeter, and its area then computed. Special instruments have been designed for this purpose.

- Gravimetric method: based on the correlation between dry weight of leaves and leaf area using predetermined leaf mass per area (LMA, determined from a sub-sample). Once the LMA is known, the entire field sample is oven-dried and leaf area is calculated from its dry-weight and the sub-sample LMA (Jonckheere *et al.*, 2004). LMA variability represents a source of uncertainty.

2.2 Indirect methods

In indirect methods, leaf area is inferred from observations of another variable. They are generally faster, amendable to automation, and thereby allow for a larger spatial sample to be obtained, thus they are becoming increasingly important (Jonckheere *et al.*, 2004).

Indirect contact LAI measurements:

- Inclined point quadrat: it consists of penetrating a vegetation canopy with a long thin needle at specific angles and counting the number of contacts with "green" canopy elements. The principal disadvantage of the method is the large numbers of points needed making the technique laborious, and its unsuitability for canopies exceeding 1.5m in height (Jonckheere *et al.*, 2004).

- Allometric techniques (for forests): based on relationships between leaf area and other dimension(s) of the woody plant element that support the green leaf biomass (e.g., stem diameter, sapwood fraction, tree height). The relationships generally are species- and site-specific and may also vary with season, site fertility (nutrition and soil water availability), local climate, and canopy structure (Jonckheere *et al.*, 2004 and references therein).

Indirect non-contact measurements:
These methods are mostly based on the measurement of light transmission through canopies, and employ various instruments developed mostly over the last 20 years. They can be divided into two groups, depending on whether they measure gap fraction distribution (proportion of area patches illuminated by direct sunlight) or gap size distribution (the size distribution of the patches). The instruments provide data that represent LAI distribution at a point location, along a line, or over an area (hemispherical photography).

- Gap fraction distribution: the existing instruments employ canopy image analysis techniques or differential light measurements above and below the canopy. The maximum measurable LAI is generally lower for these devices measuring gap fraction than the one assessed via direct methods, and reaches a saturation level at LAI=~5.

- Gap size distribution: the available instruments measure the dimensions of individual surface patches that are directly illuminated. Analytical procedures and supporting measurements are employed to convert the measurements into LAI. Hemispherical photography is one such technique.

Breda (2003) reviewed an approach of light transmittance measurement through a canopy to obtain information on daily of LAI changes within a stand.

The indirect non-contact measurements do not distinguish photosynthetically active leaf tissue from other plant elements such as stem, branches or flowers, and corrections are therefore required. Another important complicating factor is the clumping of individual needles on branches of needleleaf species which leads to LAI underestimation; correction methods have also been developed for this effect (Weiss *et al.*, 2004; Jonckheere et al., 2004 and references therein).

Following a review of the various measurement approaches and results, Jonckheere *et al.* (2004) defined the required attributes of an ideal LAI measuring device and concluded that hemispherical cameras appear to offer the greatest potential, if high spatial resolution and large signal dynamics of well registered visible and NIR bands are available; they also advocated further testing and defining of a standardized field protocol for digital hemispherical photography.

In summary, the various *in situ* LAI methods and results obtained have been described in peer-reviewed literature, and various intercomparison tests have been performed. The individual methods have specific strengths and weaknesses, and therefore are more applicable under some circumstances than others. Although general consensus seems to exist on the usefulness and applicability of the various approaches, no standards have been defined or accepted; however, common guidelines have often been developed and used by research teams collaborating in larger research programmes in various countries.

3. Existing satellite measurement methods and standards

Satellite-based estimation of LAI is an indirect approach, relying on the relationship between LAI and the characteristics of reflected radiation from the canopy as measured by the satellite sensor. Besides the process of light interaction within the canopy, the satellite data are affected by the intervening atmosphere, the characteristics and performance of the sensor, and the processing of the received signal. Various approaches have been developed to transform satellite data into LAI estimates in the form of maps. While no standardization of procedures or products has been achieved to date, progress has been made in this direction, especially through convergence of approaches to validation and intercomparisons of the various methods and products.

Morisette *et al.* (2006) reviewed the techniques employed in various countries to produce and evaluate LAI products derived from satellite measurements. They also identified the required elements for an international satellite-based products validation effort: an organizational entity, the willingness of participants to improve the consistency between methods and results, a mechanism for sharing the data along with a description of the procedure used, and the synthesis of data and results into global accuracy statements. The Land Product Validation Subgroup of the CEOS Working Group on Calibration and Validation (http://lpvs.gsfc.nasa.gov/) is leading this activity which is supported by CEOS member agencies.

4. Conclusions

1. Because of spatial and temporal variability, satellite-based methods are the only cost- effective approach to LAI estimation at landscape to global scales.
2. Due to the variability of ecosystem properties; the indirect character of satellite-based LAI estimation; and the diversity of satellite measurements and processing, LAI product intercomparisons are an essential element of a strategy for ensuring consistency and quality of global LAI products. *In situ* measurements are an integral component of such strategy.
3. Numerous *in situ* measurement techniques have been developed and used. The existing methods have been documented, and new ones are being developed (especially instruments).
4. While no definitive standards for LAI *in situ* measurements have been established, the guidelines for sampling, measurements, and data analysis have been published in peer- reviewed literature. Refinements or new methods or also continue to be developed, documented and evaluated in research programmes.

5. Recommendations

1. The systematic application of intercomparisons of satellite-based LAI products should continue to be strongly supported, including the long-term collection of LAI measurements at sites that represent the variety of vegetation canopies around the globe (with particular attention to the tropics where satellite-based methods are hampered by persistent cloudiness).
2. The establishment of consensus guidelines for LAI *in situ* measurements should be undertaken, with emphasis on the use of digital hemispherical photography.
3. The development of guidelines for the production and documentation of satellite data-based LAI products would be beneficial but further research, development and testing are required before this area reaches maturity.

6. References

Breda, N.J. 2003. Ground-based measurements of leaf area index: a review of methods, instruments and current controversies. Journal of Experimental Botany 54: 2403-2417.

GCOS. 2004. Implementation plan for the Global Observing System for Climate in support of the UNFCCC. Report GCOS – 92 (WMO/TD No. 1219). 136p.

Jonckheere, I., Fleck, S., Nackaerts, K., Muysa, B., Coppin, P., Weiss, M., and Baret, F. 2004. Review of methods for *in situ* leaf area index determination Part I. Theories, sensors and hemispherical photography. Agricultural and Forest Meteorology 121: 19–35.

Morisette, J.T., Baret, F., Privette, J.L., Myneni, R.B., Nickeson, J.E., Garrigues, S., Shabanov, N.V., Weiss, M., Fernandes, R.A., Leblanc, S.G., Kalacska, M., Sánchez-Azofeifa, G.A., Chubey, M., Rivard, B., Stenberg, P., Rautiainen, M., Voipio, P., Manninen, T., Pilant, A.N., Lewis, T.E., Iiames, J.S., Colombo, R., Meroni, M., Busetto, L., Cohen, W.B., Turner, D.P., Warner, E.D., Petersen, G.W., Seufert, G., and Cook, R. 2006. Validation of Global Moderate-Resolution LAI Products: A Framework Proposed Within the CEOS Land Product Validation Subgroup. IEEE Transactions on Geoscience and Remote Sensing 44: 1804-1817.

Weiss M., Baret, F., Smith, G.J., Jonckheere, I., and Coppin, P. 2004. Review of methods for *in situ* leaf area index (LAI) determination. Part II. Estimation of LAI, errors and sampling. Agricultural and Forest Meteorology 121: 37–53.

7.2 Biomass

Biomass estimates are essential for determining terrestrial carbon stocks and plays two major roles in the climate system:

- photosynthesis withdraws CO_2 from the atmosphere and stores it as biomass;
- quantity of biomass consumed by fire affects emissions of CO_2 and of other trace gases and aerosols.

Biomass change (due to land use and management practices or to natural processes) provides a direct measurement of carbon sequestration or loss and can help to validate carbon-cycle models (GCOS, 2006).

1. Definition and units

Biomass is defined as mass per unit area of living plant material.
Unit of measure is g/m^2 or kg/ha.

2. Existing measurement methods and standards

Only above-ground biomass is measurable with some accuracy at the broad scale. While below-ground biomass stores a large part of total carbon stocks, it is rarely measured because it can only be assessed through *in situ* measurements that tend to be labour- and time-intensive (GCOS, 2003).

There are four main ways to monitor biomass, discussed in more detail below:

a. Destructive sampling (*in situ*).
b. Non-destructive sampling for forest inventories (*in situ*).
c. Inference from remote sensing (experimental stage).
d. Models.

For each of these methods**, allometric equations** are used to extrapolate sampled data to a larger area. Allometry relates the size of one structure in an organism to the size or amount of another structure in the same organism; for example, relating the diameter of a tree trunk to the amount of biomass in that tree. Allometric equations can be applied to one or more variables (such as tree height, diameter, age, and vegetation type or structure) derived from forest inventories or from remote sensing images. Published allometric equations for specific vegetation types are often used, but because allometric coefficients vary between sites and species, the use of standard allometric equations can lead to significant errors in vegetation biomass estimations (Heiskanen, 2006; Australian Greenhouse Office, 1999).

a. <u>Destructive sampling</u>

This method entails harvesting trees (including the roots), drying them, and then weighing the biomass. These measurements of forest biomass can be aggregated for a small sample area, or extrapolated to wider levels using allometric equations. While this is the most direct and accurate method for quantifying biomass within a small unit area, it is expensive, time-consuming, and infeasible at the country-level.

b. <u>Non-destructive sampling</u>

This includes sampling measurements that do not require harvesting trees, such as height and trunk diameter and uses allometry to extrapolate biomass.

c. Inference from remote sensing

Biomass can be inferred directly or indirectly (relating tree height or other variables to biomass with allometric equations) from satellite and airborne imagery. There are two ways of estimating biomass from satellite or aircraft data. The first method uses data such as Landsat Thematic Mapper (TM) data to determine the area of woody vegetation across a given scale, then stratifies the total area into classes that are relatively homogenous in terms of biomass (such as structural vegetation types), and then attributes an average biomass density (kg/ha) to each. The classification systems for vegetation must be based on attributes that are easy to discern from remotely sensed data, such as crown cover classes, genus and major species, growth form (tree, shrub, etc.), and height. In assigning an average biomass density to each strata (vegetation class), it may be necessary to gather additional field data in order to validate that biomass estimates for a stratum in one part of a country or region are valid in another (Australian Greenhouse Office, 1999). As biomass density is affected by the stage of development, it may also be necessary to apply a factor to biomass estimates to account for different growth stages within strata.

The second method uses a process model to estimate the amount and distribution of biomass, predicted from known relational variables, to derive spatially continuous biomass estimates (Australian Greenhouse Office, 1999). For example, Graetz (1988) discerned a relationship between above- and below-ground biomass density and the annual mean soil moisture index.

d. Models

Models have been used to derive biomass estimates with limited frequency and intensity of *in situ* or remotely sensed inventory. These are generally empirical models based on a network of repeatedly measured sample plots, which may have biomass estimations built in or may required allometric relationships to convert volume to biomass. Because such models do not exist for most forested areas, process models that are based on multiple environmental variables and are calibrated to account for different vegetation types may be optimal (Australian Greenhouse Office, 1999).

2.1 *In situ*

In situ measurements should be conducted every five years and can generally measure biomass with an accuracy of 10 percent to 20 percent (GCOS, 2006).

In situ measurements are critical to the monitoring of terrestrial carbon stocks, but they impose many limitations. They are generally labour-intensive and expensive, and there are many other problems, including incomplete data, inconsistent parameter definitions, inconsistent spatial and temporal scales, and sampling bias in measurements (IGOS, 2004).

Many developed countries have had forest inventories containing large numbers of sampling locations for decades, but many forest biomes elsewhere have little or no inventory data (IGOS, 2004; GCOS, 2003). Countries with existing forest biomass inventories typically use these as the basis of their forest resource reporting to the UNFCCC. These have generally been developed for forestry and agricultural purposes (not for carbon measurement) at the national and sub-national levels, and there have not until recently been efforts to coordinate and harmonize these inventories internationally. As a result, there is a high degree of inconsistency among the inventories with regard to definitions, standards, type of data collected, and quality (IGOS, 2004). The only available global gridded biomass data set is that from the World Resources Institute, based on existing databases supplemented by satellite observations. The accuracy, resolution and currency of this data set are unknown (GCOS, 2003). Most detailed *in situ* biomass data are not readily available or are only available as highly aggregated summaries. Country-by-country summary statistics are available and FAO's Forest Resources Assessment (FRA) 2005 has provided the first global data set on forest carbon, however biases and uncertainties in these summary values are not quantified (FAO, 2001; FAO, 2006). The global FRA 2010 will provide an updated data set.

Assessment of below-ground biomass is particularly challenging because (as it cannot be measured from satellites), it requires an increased density of *in situ* observations and improved scaling algorithms (FAO, 2001). The only global inventory providing below-ground biomass information is the FAO/UNESCO soil map of the world (based on soil surveys performed in the 1960s). Several regional updates of the map have been undertaken using the SOTER approach (FAO, 2001).

With the rising importance and increasing sophistication of satellite methods for biomass estimation, *in situ* methods remain important as a means of "ground truthing" satellite measurements. As such, efforts to improve *in situ* data collection should be integrated with remote-sensing observations to improve accuracy and provide internal validation.

2.2 Satellite

Satellite technology allows for increasingly frequent measurement of biomass. Satellites sample with varying frequencies (e.g. monthly averages), but temporal sampling points throughout the year should be compared with yearly repetition.

Satellite approaches to estimating biomass are still in experimental stages and of uncertain accuracy. However, several satellite methods have demonstrated potential for providing direct and indirect global above-ground biomass information at high resolution (below 1 km), and will become increasingly important to biomass monitoring (TEMS; IGCOS, 2004; GCOS, 2003).

The direct approach infers biomass directly from the signal, while the indirect approach measures forest height or another variable and applies an allometric relation to arrive at a biomass estimate.

The Integrated Global Carbon Observing System Implementation Plan (IGCOS, 2004) identifies three remote-sensing technologies that are especially promising for improved biomass estimates:

The direct measurement instrument, **long-wavelength radar,** has proved to be ideal for mapping of several forest biomes. The ALOS L-band SAR (launched in early 2006) should provide the first systematic global observations for generating biomass maps. However, the temporal and spatial resolution, and the conditions of observation (e.g. incident angle) are different from one satellite to another. Currently, the lowest frequency that can be used for spaceborne SAR is P-band (i.e. for planned ESA-BIOMASS mission). P-band backscatter has been shown to be sensitive to forest biomass up to a saturation level of 100 to 150 t/ha, making it suitable to map the biomass of most of the boreal forest and a large part of the temperate forests (but not the biomass levels found in the tropics) (GCOS, 2003; IGCOS, 2004). The saturation of radar backscatter alone at higher levels of biomass is a known limitation of these technologies. However, advanced SAR technologies, i.e. integration of multi-temporal observations (Kurvonen *et al.*, 1999), interforemetric SAR using C-, L-, and P-band (Santoro *et al.*, 2002; Askne *et al.*, 2003; Wagner *et al.*, 2003), and very high frequency SAR, though limited to airborne sensors (Israelsson *et al.*, 1997; Fransson *et al.*, 2000) have proven further potential for forest biomass mapping up to at least 200 m^3/ha (Santoro *et al.*, 2002, 2006).

The indirect technologies measure forest height, and apply local or regional allometric relationships to estimate biomass: **Airborne lidar systems** and **L-band SAR polarimetric interferometry**. Airborne lidars produce spaced samples along transects, generating spatially explicit maps that must then be extended through radar imagery (IGCOS, 2004). L-band SAR polarimetric interferometry provides more rigorous measurement of biomass than C-band, though it is still limited to 50-70 t/ha and therefore most suitable for mapping the biomass of low productivity or young forests (IGCOS, 2004; IGOS, 2004; FAO, 2001).

The Integrated Global Observing Strategy (IGOS) has developed an implementation plan to create a coordinated system of integrated global carbon cycle observations, through the harmonization of existing components and the development of new components. The initiative would collaborate with national and international forest inventory initiatives, such as FAO's Global Resources Assessment programme and its programmes to support national forest assessments and inventories. The objectives would be to harmonize the data from various countries, and report them in a transparent and verifiable manner to form a consistent global dataset for carbon accounting purposes. Over land, the carbon observing system would make repeat measurements (at five-year intervals) of above-ground biomass in sample plots in all major forest biomes including both unmanaged and managed forests in the tropics, the temperate and boreal zones (IGOS, 2004). FAO's global Forest Resources Assessment 2010 and subsequent assessments which are carried out every five years will be fundamental in developing complete, accurate and consistent global datasets.

Efforts to create continuous, standardized, geo-referenced forest biomass inventories will require harmonizing the widely varying methodologies for data collection and analysis. The standard methodology for biomass values for use in grid cells should include:

- Minimum, maximum, mean, median, standard deviation, estimation protocol, number of points included.
- Biomass by root, folia, stem, and branch components.
- Time period represented by the biomass estimates (IGCOS, 2004).

For remote sensing of biomass, the adoption of a single land classification system, such as the Land Cover Classification System (LCCS), would increase consistency among measurements and enhance standardization efforts. LCCS, for example, is in the process of being linked to designated biomass values that will allow for automatic biomass estimates by land cover type (FAO, 2005).

Another major observational challenge is to establish allometric functions to convert above-ground biomass to total biomass (IGOS, 2004).

3. Conclusions

1. There are large gaps in available data on biomass in terms of inclusion of above and below ground components, spatial and temporal consistency, and completeness in both spatial and temporal dimensions (FAO, 2001).
2. The *in situ* inventory agencies and remote sensing agencies must work together to allow validation and upscaling of the *in situ* measurements based on the remote sensing products (IGCOS, 2004).
3. To increase the quantity of below-ground biomass observations, new soil carbon estimation techniques must to be developed that combine *in situ* and modelling strategies.

4. Though still under development, satellite-based methods are very important for quantifying above-ground biomass and its changes at high spatial resolution. The most promising of these are long-wavelength radar, lidar, and radar interferometric techniques.

4. Recommendations

1. *In situ* measurements for biomass should be conducted every five years, and remote sensing measures should be conducted on an annual basis.
2. Improve the quality and quantity of *in situ* monitoring above- and below-ground biomass estimates in order to validate remote sensing derived data.
3. Expand forest biomass inventories to tropical forests, non-commercial forests, and woodlands.
4. Develop new soil carbon measurement techniques and sampling strategies.
5. For below ground-biomass, increase the density of *in situ* observations: i) by improving or adding observations within existing networks; ii) by significantly expanding the soil profile databases available through SOTER and similar programmes, and iii) through more efficient use of national inventories, in combination with land cover derived from satellite data. Deployment of biomass surveys to obtain full coverage of forest ecosystems, particularly in the tropics, is necessary.
6. Full advantage should be taken of existing and planned satellite SAR missions including historical data (JERS-1, ERS-1/2 interferometry), current sensors (multitemporal ENVISAT-ASAR, ALOS-PALSAR) and support future missions (ALOS follow-up, ESA-BIOMASS).
7. For remote sensing estimation of biomass, use a single classification system, such as the Land Cover Classification System (LCCS).

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7.3 Glaciers

Changes in mountain glaciers and ice caps provide some of the clearest evidence of climate change, constitute key variables for early-detection strategies in global climate-related observations and cause serious impacts on the terrestrial water cycle and societies dependent on glacial melt water (GCOS, 2004).

1. Definitions and units

Glacier is defined as a mass of land ice flowing downhill (by internal deformation and sliding at the base) and constrained by the surrounding topography (e.g. the sides of a valley or surrounding peaks); the bedrock topography is the major influence on the dynamics and surface slope of a glacier. A glacier is maintained by accumulation of snow at high altitudes, balanced by melting at low altitudes or discharge into the sea (IPCC, 2001). **Ice cap** is a dome-shaped ice mass covering a highland area (less than 50,000 km^2 of land area) that is considerably smaller in extent than ice sheets (IPCC, 2001). Since the same measurement principles are applicable to both, the term "glaciers" is used below to represent both features.

To determine glacier changes, two primary variables must be measured: surface area, and annual mass balance.

- Surface area: area of a glacier (km^2);
- Annual mass balance: change in the mass of a glacier (m^3/yr).

Other variables are also important for understanding glacier behaviour and the processes causing annual changes. They include (e.g. Dyurgerov, 2002):

- winter and summer balances;
- net accumulation and net ablation;
- annual accumulation and ablation;
- mass turnover;
- equilibrium-line altitude;
- accumulation-area ratio;
- and others (IGOS, 2006).

Dyurgerov (2002) also discussed the definitions of these variables and their determination using available measurements.

2. Existing *in situ* measurement methods and standards

<u>Surface Area</u>

To identify surface area, the boundaries of a glacier must be identified. This is typically done with the use of air photos or satellite images. For example, the current Global Land Ice Measurements from Space (GLIMS) project considers the following boundaries for glaciers mapped using space-based EO data (GLIMS Algorithm Working Group, 2006): clean ice, rock, debris, debris-covered ice, snow, clouds, sea ice.

Glacier surface area is typically determined from aerial photographs or satellite data and is therefore subject to inaccuracies, including inconsistencies among interpreters. To avoid such inconsistencies, the GLIMS project adopted the following definition tailored to remote sensing (not involving ice motion): “A glacier...consists of a body of ice and snow that is observed at the end of the melt season, or, in the case of tropical glaciers, after transient snow melts. This includes, at a minimum, all tributaries and connected feeders that contribute ice to the main glacier, plus all debris-covered ice. Excluded is all exposed ground, including nunataks. An ice shelf - ice downstream of the grounding zone of two or more glaciers that is floating on ocean
water - shall be considered as a separate glacier” (GLIMS, 2006, p.4).

The GLIMS project developed a set of software tools used to track several glacier variables using data from the ASTER instrument onboard the Terra satellite: areal extent, location of snow line at the end of the melt season, velocity field, and location of terminus (www.glims.org).

Changes in surface area are determined by repeated glacier area mapping or (for satellite data) through change detection image analysis procedures.

Müller *et al.* (1977), Müller (1978), and Scherler (1978) described procedures to be used in the compilation of a database, the world glacier inventory (http://nsidc.org/data/glacier_inventory/); this inventory is a compilation of data on provided by individual countries and other sources. Dyurgerov (2005) calculated mass balance for glaciers outside the Greenland and Antarctic ice sheets.

Annual mass balance

Kaser *et al.* (2002) listed and briefly described eight different approaches for determining glacier mass balance:

1. The geodetic method (considered useful complementary to the glaciological method and over larger time steps (e.g. ten years) as a check on the field-based methods);
2. The glaciological method (considered the most accurate method which provides the most detailed information on the spatial variation of mass balance magnitudes, but requiring repeated field measurements with slow rate of data acquisition and high expenses for logistics and labour). Dyurgerov (2002) explained this method in more detail, and Kaser *et al.* (2002) described procedures for *in situ* measurements.
3. Indirect methods diverted from the glaciological method (requires a long time series of data (~5-10 years) and is not suitable for programmes without such a background of data);
4. The flux method (holds only for steady state conditions, and fails under both acceleration (as a consequence of positive mass balances) and slowdown (negative mass balances) conditions);
5. The hydrological method (requires good instrumentation to measure each of several hydrological variables, challenging for unattended operation; extrapolation of precipitation from a single gauge to the surrounding mountainous terrain is often inaccurate; the natural processes of storage and release of water within a glacier can confound this method; thus, the hydrological method is usually applied only in conjunction with other methods); the flux-divergence method (combination of geodetic method and dynamic ice flow models; it fails because of the inability of dynamic models to derive sufficiently accurate vertical ice velocities; also, depends on airborne instruments, which are expensive and subject to bad weather conditions);
6. Modeling from climate records (because of the complexity of precipitation distribution and accumulation, most models rely on a simple extrapolation from precipitation data; models have

to be calibrated for the glacier in question and thus mass balance data are needed, at least in the beginning).

Dyurgerov (2002) discusses the issues and approaches applicable to various degrees of upscaling to global extent, and identified the following deficiencies of the current global glacier inventories (refer to supporting information therein):

1. Glacier inventory data exist for only for about 10-20 percent of all glaciers in the world.
2. Glacier area is subject to constant change in time.
3. Area of individual glaciers around Antarctic Ice Sheet has not been determined yet.
4. It is difficult to compare the very short mass-balance time-series on glaciers in many regions (Russian Arctic Islands, individual glaciers around Greenland Ice Sheet, Sub-Antarctic, Himalayas, New Zealand, Iceland, South America), with the relatively long-time series in Europe, North America, Canadian Archipelago, and mountain chains in the southern part of Former Soviet Union (Caucasus, Tien Shan, Pamir, Altai). This unequal spatial and temporal coverage makes global assessment very complicated; in addition, the global estimation may be biased toward maritime climate conditions, as more than 60 percent of long-term mass balance records are from the Alps, Scandinavia, and northwestern Northern America.
5. The lack of data on mass balance of very large glaciers (Alaska, Central Asia, Patagonia Ice Fields), which may have different mass balances compared to the small and medium-size glaciers that are commonly used for mass balance study.
6. Very small glaciers, those less than 1 km^2 in area, are poorly inventoried and their regime may be different from that of larger glaciers. The extreme turnover value (about 20 m/yr in water equivalent) and huge interannual variability of snow patches (nearly glaciers) and their unknown total area may be important in some regions.

The World Glacier Monitoring Service (WGMS) assembles information on glaciers provided from many countries, and it publishes reports on glacier fluctuations approximately every two years. Their quality and completeness depends on the data provided to the WGMS, and therefore these reports show gaps in coverage (in both space and time). Mass-balance records have been published between 1967 and 1998 in seven volumes by the WGMS, and every two years since 1991 (www.geo.unizh.ch/wgms/). The World Glacier Inventory, based on the WGMS data, contains information for over 67 000 glaciers throughout the world with one-time information on geographic location, area, length, orientation, elevation, and classification of morphological type and moraines (http://nsidc.org/data/g01130.html). Syntheses and analyses of data reported by the WGMS and data from other sources (e.g. research programmes and archives) are occasionally analysed to establish trends over larger areas. In this process, upscaling of measurements of individual glaciers to larger regions presents a significant challenge.

To obtain information on individual glaciers, the WGMS specifies the format and content of national inputs; these are available at www.wgms.ch/datasub.html. In November 2006 the WGMS issued “Guidelines for the call-for-data for the observation period 2000– 2005” that are available at this Web site. The guidelines specify that the following types of information be provided (among others):

1. General information (including glacier name, hydrological catchment area, location, primary classification [icefield, valley glacier, etc.], form [compound basin, cirque, etc.], frontal characteristics [piedmont icefield, single lobe, etc.]).

2. State (including elevation, length, survey method [Aerial photography; Terrestrial photogrammetry; Geodetic ground survey; Combination; Other].

3. Front variation (including qualitative (advance, retreat, stationary), survey method [same as for State], etc.).

4. Data sheet (including boundaries, area, thickness, volume and their changes by altitude interval; survey method [as for State], etc.).

5. Mass balance overview (including beginning and end of survey period, equilibrium line altitude, accumulation area, ablation area, etc.).

6. Mass balance (including specific winter and summer balance, etc.).

7. Special events (date, type [e.g., glacier surge, caving instability, ice avalanche, etc.] and description, etc.).

While the reporting of *in situ* glacier observations is standardized in this manner by the WGMS, there appear to be no generally accepted standards or guidance documents for making these measurements. The WGMS guidelines contain a list of candidate methods (see b), c), d) above) but also makes provision for "Other" methods which are to be described if used. In general, the developers and users of *in situ* methods appear to be concerned with the accuracies, costs, and practicalities involved in the use of such methods. There is no indication that one approach should be used in all circumstances, although the glaciological method is considered to be the most accurate (Kaser *et al.*, 2002).

For many years, the WGMS has been the principal mechanism for assembling and reporting on glacier changes at the global level and in a standardized manner. However, its operation has been hampered by inadequate and uncertain funding. At present, only a two-year bridge funding is available from the Swiss National Science Foundation. The WGMS submitted a proposal to the Global Earth Observation System of Systems (GEOSS) for 10-year funding, but so far received no response. A secure financial basis of about US$250 000 is needed by the WGMS to ensure the continuation of operational business, to maintain the international network and the reporting functions.

3. Existing satellite measurement methods and standards

Surface Area

The most frequent use of satellite data has been for surface area measurement. Higher resolution imaging data types (Landsat Thematic Mapper and ETM+, SPOT HRV, Terra ASTER) are typically used. In the largest project of this type to date, the Global Land Ice Measurements from Space project (GLIMS), has undertaken to map all land-based glaciers of the world (estimated to be about 160 000, twice as many as captured by the WGMS to date; Bishop *et al.*, 2004; www.glims.org/).

GCOS (2006) specified the following target requirements for products showing the areas covered by glaciers (other than ice sheets):

- Accuracy: 5 percent (maximum error of omission and commission in glacier are maps); location accuracy better that 1/3 instantaneous field-of-view (IFOV) with target IFOV of 30m.

- Spatial and temporal resolution: 30m horizontal resolution, one-year observing cycle; for the historical perspective, several years of observations are required to build up and inventory in regions with frequent could cover.
- Stability: 5 percent (maximum error of omission and commission in glacier map areas); location accuracy better than 1/3 IFOV with target IFOV 30m.

Mass balance

Active optical and microwave sensors have been employed experimentally to estimate glacier volume changes or parameters related to it. These approaches have not yet been refined to the degree where they can provide operationally reliable alternative to field measurements. However, aircraft-based measurements have been employed successfully to quantify glacier and ice sheet changes. Desirable monitoring approaches consist of satellite altimetry, complemented by observations of flux divergence from repeated interferometric surveys using synthetic aperture radar and gravity measurements of ice mass change; the planned missions will allow improved estimates of ice sheet elevation change but the needed spatial resolution requirement at the margins will only be achieved by development of an acquisition strategy for fine-resolution missions (CEOS, 2006).

Except for the GLIMS project (see above), no general standards or guidance documents have been found for mapping surface area or mass balance from space-based EO data.

The cryosphere theme report (IGOS, 2006) identified the following observation requirements for glaciers:

Parameter	C T O	Measurement Range			Measurement Accuracy		Resolution				Comment / Principal Driver
							Spatial		Temporal		
		L	H	U	V	U	V	U	V	U	
Area	C				1	%	5	m	30	a	airborne
	O				3	%	30	m	5	a	Landsat etc. Hi res. optical
	T	0.01	5000	Km2	3	%	50	m	5	a	
	O	0.01	5000	Km2	1	%	15	m	1	a	
Topography	O										Airborne
	C	0	8500	m sl.	5	m	100	m	5	a	For models
	T	0	8500	m sl.	0.1	m	30	m	1	a	Mass balance
Velocity	O				1	%	point		1	a	In situ
	C	0	10	Km/a	5	%	200	m	1	a	InSAR etc.
	T	0	10	Km/a	1	%	50	m	1	m	
Glacier dammed lakes					1	%	1	m	1	a	airborne
		0.05	10	Km2	3	%	50	m	1	m	SAR, hi res. optical
		0.01	10	Km2	1	%	15	m	5	d	
Facies, snowline	C						point				In situ
	T			class	200	m	100	m	1	m	Position of boundary
	O			class	30	m	30	m	10	d	
Accumulation	C				5	%	point				In situ
	T	0.05	8	m	10	%	500	m	1	a	Ku-, X-SAR
	O	0.10	5	m	5	%	100	m	1	m	
Mass balance	C				0.10	m	point				In situ
	T	0	±5	m	0.20	m	500	m	1	m	process model & SAR
	O	0	±5	m	0.05	m	100	m	1	a	
Ice thickness	C										In situ
Ice cores	C										In situ
	O										

4. Conclusions

1. In addition to two key glacier variables identified in the GCOS Implementation Plan (GCOS, 2004) several other variables need to be measured for a spatially and temporally representative analysis of glacier response to climate change.

2. Measurements of surface area are based on various approaches. They have not been standardized, but this may only need to be required except for minimum accuracy and similar attributes, as areas may reliably be determined in different ways.
3. Several methods are used for *in situ* measurements of mass balance, with different trade-offs regarding accuracy, cost, required instrumentation, and logistics. Some methods continue to be developed, including those based on airborne or spaceborne measurements. Although the glaciological method is considered to be most accurate at present, no single method has been endorsed as a standard.
4. Available literature and expertise appear to provide sufficient basis for preparing guidance documents to increase the compatibility of *in situ* glacier measurements carried out in different countries, but the development of space-based methods is not sufficiently advanced in that respect (especially for mass balance measurements).
5. The World Glacier Monitoring Service (WGMS) is the principal mechanism for assembling and reporting on glacier changes at the global level and in a standardized manner; however, its continuing operation is threatened by the absence of a long-term financial commitment to support this essential activity.

5. Recommendations

1. For surface area, guidance documents should be prepared specifying performance requirements for airborne and space-borne methods.
2. For mass balance, the feasibility of establishing a registry of *in situ* methods for mass balance measurements should be evaluated and, in the affirmative case, a registry should be set up which specifies the performance requirements and technical details of individual methods suitable for this purpose.
3. The list of supporting glacier measurements required for climate change purposes should be prepared and, where appropriate, measurement guidelines developed and published.
4. In addition to measurement standards, the scope and representativeness of glacier measurements continue to be of serious concern. These issues have been previously raised by GCOS (GCOS, 2004, 2006) but remain to be satisfactorily addressed. They include adding observational sites and infrastructure in South America, Africa, the Himalayas and New Zealand, re-initiation of mass balance measurements of certain critical glaciers and ice caps, and urgent need to blend surface observations with satellite-based optical and microwave satellite data.
5. As a matter of priority, the governments and international agencies concerned with climate change impacts should identify funds required for the continuing operation of the World Glacier Monitoring Service, as the main mechanism for assembling and publishing information on glacier changes around the world.

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7.4 Acronyms

ALOS	Advanced Land Observing Satellite
ASAR	Advanced Synthetic Aperture Radar
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CEOS	Committee on Earth Observation Satellites
CO_2	carbon dioxide
COP	Conference of the Parties
DAAC	Distributed Active Archive Center
ECV	Essential Climate Variable
Envisat	Environmental Satellite
EO	Earth Observations
ERS	European Remote Sensing satellite
ESA	European Space Agency
ETM+	Enhanced Thematic Mapper
FAO	Food and Agriculture Organization of the United Nations
FAPAR	Fraction of absorbed photosynthetically active radiation
FRA	Forest Resources Assessment
GCOS	Global Climate Observing System
GEOSS	Global Earth Observation System of Systems
GLIMS	Global Land Ice Measurements from Space
GOFC-GOLD	Global Observation of Forest and Landcover Dynamics
GOSIC	Global Observing Systems Information Center
GRDC	Global Runoff Data Center
GTOS	Global Terrestrial Observing System
HRV	Haoute Resolution Visible (High Resolution Visible Imaging System)
IFOV	Instantaneous Field Of View
IGBP	International Geosphere-Biosphere Programme
IGCOS	Integrated Global Carbon Observing Strategy
IGOS	Integrated Global Observing Strategy
IPCC	Intergovernmental Panel on Climate Change
JERS	Japanese Earth Resources Satellite
LAI	Leaf Area Index
LCCS	Land Cover Classification System
LMA	Leaf Mass per Area
NASA	National Aeronautics and Space Administration (US)
NIR	near-infrared
PALSAR	Phased Array type L-band Synthetic Aperture Radar
SAR	Synthetic Aperture Radar
SBSTA	Subsidiary Body for Scientific and Technical Advice
SOTER	Global Soil and Terrain Database
SPOT	Satellite Pour l'Observation de la Terre
TCF	Terrestrial Climate Framework

TEMS	Terrestrial Ecosystem Monitoring Sites database
TM	Thematic Mapper (Landsat)
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
USGS	United States Geological Survey
WDC	World Data Center
WGMS	World Glacier Monitoring Service
WMO	World Meteorological Organization