Remote Sensing of Biomass: Principles and Applications

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1. Introduction.

Remote sensing is an important tool in determining the area and type of above-ground land-based biomass. Such information is required to compare supply and demand, determine the rate of deforestation and its causes, assess the store of carbon in biomass and the potential for increasing the store and use etc. The various types and uses of remote sensing are discussed together with their limitations, costs and benefits. This article is limited to land based biomass determination, although about half the net primary production (NPP) from photosynthesis is produced in the oceans. Only a few water-grown plants, algae and bacteria are used or have potential for use and so this will not be included, except such biomass as mangroves, coastline saline crops such as halophytes and deep-water rice.

Remote sensing cannot be used alone to determine the quantity and yearly yields of annual and perennial plants, nor can it be used to determine the amount of animal biomass, especially dung, some of which is used for energy and other purposes. Thus, methods of ground truthing are described to complete the equation for determining the quantity, quality and uses of different types of biomass growing or produced on all land types (Table 1.1 and 1.2).

Table 1.1. Land-use categories recognized in FAO's World Agriculture Census

Land-use categories	Short description
(a) Deserts (barren land and waste land	Deserts
(b) Non-forest woodlands (rangeland/ scrubland; may include national parks and wilderness recreational areas)	Rangeland/ scrubland
(c) Wetlands, Non-Forest (marshes)	Wetlands
(d) Land under forest (natural forests and most woodlands)	Forest land
(e) Land under forestry/silviculture	Managed forests
(f) Land under shifting cultivation (forest land temporarily cleared to grow agricultural crops for a short time period and then allowed to revert to forest, before the cycle is repeated	Shifting cultivation
(g) Land under Agroforestry (permanent use at holding level, but with mixed crops growing, animal herding, and tree growing	Agroforestry
(h) Land with temporary fallow. (resting for a period of time, less than 5 years, before it is again planted with annual crops)	Fallow
(i) Land under permanent meadows and pastures (used for herbaceous forage crops that are either managed/cultivated [pastures] or growing wild [grazing land]; trees and shrubs may be present or grown purposely, but the forage is the most important use of the area; grazed woodlands)	Grasslands and rangelands
(j) Land under temporary meadows and pasture (cultivated temporary for less than 5 years, for herbaceous forest crops, mowing or pasturing, in alternation with arable cropping)	Temporary meadow
(k) Land under permanent crops (perennials; cultivated with long-term crops that do not have to be replanted for several years; harvest components are not wood, except at the replanting stage, but fruit, latex, and other products that do not significantly harm the growth of the planted trees or shrubs/bushes; orchards, vineyards, rubber and oil palm/coconut plantation, coffee, tea, sisal, etc.)	Perennial cropland
(l) Land under temporary crops (annuals; cultivated with crops with a growing cycle of under 1 year, which must be newly sown or planted for further production after harvest; not only grain crops, but legumes, beets and tobacco, but also bi-annuals that are destroyed at harvest at harvest, such as cassava, yams and sugarcane; bananas are transitional to the permanent crop category)	Cropland
(m) Land under temporary crops requiring wetland conditions (wet-food crops such as irrigated rice and jute [dry food crops with intermittent irrigation included in other categories])	Riceland etc.
(n) Land under protective cover (greenhouses, and other urban or peri-urban intensive use, formal or informal; market gardening, home gardening, residential parks, golf courses etc.	Per-urban land
(o) Land under residential/industrial/transportation facilities	Built-up areas

Source. IPCC 2001 (Intergovernmental Panel on Climate Change). Chapter 2. Table 2.1; FAO 2005.

In this article, land use, and ground cover will be the principal classifications of land types: sometimes they are used interchangeably. Table 1.1 gives the broad land use types as defined by the Food and Agricultural Organization of the UN (FAO) for their agricultural census. This contains fifteen (15) broad land use types in order of increasing use intensity. There are sub-divisions, some of which are given in the table, such as coconut, tea and coffee under (j) above: these are woody in composition. Most areas have woody biomass on them or along their borders. This is why it is important to survey such areas, especially as they may be an important product source, especially woodfuel and poles from agricultural land.

The types of arable crops may be distinguished, whether single species or mixed species. Also, with irrigation there may be up to three crops per year. For the world as a whole, with a total land area of 14,894 million ha, forests occupy 27%, other wooded areas 8%, arable land 11%, grasslands including wetlands, 28%, deserts 12%, built up areas etc. 2% and the arctic regions 12%.

For an analysis of woody biomass, a more detailed breakdown of the land use under trees may be required. Table 1.2 gives a broad classification as follows:-

Table 1.2. Land-use categories containing trees.

Land-use categories with trees	Short description
Trees in closed formations: Crown cover > 10%	
(a) Boreal (subarctic zone containing conifers and evergreen)	Boreal
(b) Temperate forest (deciduous, conifers, mixed & rainforests)	Temperate
(c) Sub-tropical (moist, dry; deciduous, evergreen, conifer, mixed)	Sub-tropical
(d) Tropical (moist, dry; deciduous, evergreen, conifer, mixed)	Tropical
(e) Plantations/woodlots in zones b, c, & d (deciduous, conifers)	Plantations
(f) Shifting cultivation (tropical and sub-tropical forests)	Shifting cultivation
(g) Mangroves.	Mangroves
(h) Bare land to be regenerated or replanted	Bare forest land
Relatively dry areas. Crown cover can be as little as 10%	
(i) Woodlands in zones b, c & d (open, moist, dry miombo, seasonal)	Woodlands
(j) Bushland & Thicket (Dry and moist Acacia-Commiphora Bush & Thicket)	Bushland/Thicket
(k) Shrubland	Shrubland
Trees outside the 'forest'	
(l) On-farm in agro-forestry formations (arable)	Agro-forestry
(m) On-farm (arable) in non-agro-forestry formations, (shelterbelts, copse, clumps, hedges, wind breaks, scattered trees etc.)	On-farm trees
(n) Trees on grasslands, pastures and wastelands (in agro-pastoral formations, clumps, hedges, windbreaks, scattered trees etc.)	Grassland trees
(o) Wetland trees	Wetland trees
(p) Trees along road, rail and river, paths	Roadside tress etc.
(q) Trees in towns, parks, gardens etc.	Miscellaneous trees

Source. ESMAP/WB. 1991; IPCC. 2000; FAO. 2010a; Author's input.

Of course, these broad groups may be sub-divided. One country or region will only have a few of the forest types mentioned above. However, in an inventory that was undertaken in sub-Saharan Africa, 40 categories of land-use types containing tree, bushes or shrubs were recognized (ESMAP/World Bank [WB][1] 1991). Thus, the level of detail required for land-use types will determine the intensity of remote sensing.

2. Remote Sensing[2].

There are two broad types of remote sensing, namely aerial photography and satellite imagery. These are now discussed. Aerial photography is usually taken from a fixed-winged light plane or a balloon etc. at a specified distance close to the ground, therefore considerable details can be shown of the ground cover and in some cases it is possible to measure heights and crown diameters of trees. On the other hand, satellites are many hundreds of kilometres in the sky on a fixed orbit and do not take into consideration changes in altitude of the land masses. However, the latest resolutions from these satellites can give an image as small as 2.5 meters square, so detailed changes of ground cover over the seasons and over time can be monitored.

2.1 Aerial Photography.

Aerial photographs**,** as the name indicates are taken from an aircraft or balloon etc. and they give a bird's eye view of the earth. They are not maps, but can be used in the preparation of maps. They give a permanent record of the area in question and are a powerful tool in the study of the environment. They are an excellent data source for monitoring land use and land use changes over time. They can be and are incorporated into the geographical information system (GIS). The advantage over ground-based observations, apart from providing a permanent record, are that it offers an improved

[1] Joint World Bank/UNDP: Energy Sector Management Assistance Programme (ESMAP).

[2] This section relies heavily on *Assessment of Biomass Energy Resources: a Discussion on its Need and Methodology,* Ryan, P.A. Openshaw, K. (1991). The World Bank Industry and Energy Department Energy Series Working Paper 48, December 1991 and a web search of NASA, NOAA and SPOT.

vantage point, it has a broader spectral sensitivity than the human eye and it has better spatial resolution and geometric fidelity than many ground-based sensing methods. Originally all photographs were black and white, but today coloured photographs, especially, coloured infrared, are favoured, because vegetation types can be distinguished, especially if the data are digitally sensed. Aerial photography has the advantage that it can take photographs of specific areas and areas that usually have cloud cover on cloud-free days. The author used this method to take photographs of different agricultural areas in Kenya to determine the sampling sites for an inventory of farm trees.

Today, aerial photography is largely confined to urban settings, but it is used for forest inventory, usually at a scale of 1:20,000 to 1:50,000 over a limited area (up to 300,000 ha), especially in tropical high forests. It is expensive per unit area (US$ 10-12 per km^2 [100 ha] for 1:40,000 panchromatic photos), but it provides a basis for more detailed delineation of vegetation types and even individual trees. With larger scale photography, tree height and/or crown diameter could be measured in more open stands. Many government departments have time-series of aerial photograph of specific areas. They are an important historic record and with today's satellite imagery can monitor land use changes over time.

2.2 Satellite Imagery.

Satellite imagery of land cover has primarily replaced aerial photography. There are three principal systems namely:

1. Advanced Very High Resolution Radiometry/Infrared Radiation (AVHRR/IRR) on the NOAA weather satellites, (the US National Oceanic and Atmospheric Administration). This gives low resolution imagery with a resolution of one to eight km.
2. LANDSAT TM (Thematic Mapper) and MSS (Multi-spectral Scanner) imagery, from NASA (the US National Aeronautics and Space Administration) and the US Geological Survey (USGS). This gives higher spatial resolution imagery (resolution 30 to 80 m). Today, Landsat Enhanced Thematic Mapper (ETM), which was launched in 1999, has resolutions of 30 m for multispectral (ms) and 15 m for panchromatic (pan).
3. SPOT imagery. SPOT image is a public limited company created by the French Space Agency, Centre National d'Etudes Spatiales (CNES), the Institut Geograhique National (IGN) and Space Manufacturers. It is a 99% subsidiary of EADS Astrium (European Aeronautic Defence and Space Company N.V.). The company is the commercial operator for the SPOT Earth observation satellites. Again this gives high spatial resolution imagery (resolution of 20 m for multispectral (XS) imagery and 10 m for panchromatic (XP) imagery). In May 2002, SPOT 5 satellite was launched. Compared to its predecessors, SPOT-5 offers greatly enhanced capabilities. The coverage offered by SPOT-5, namely 2.5, 5, 10 & 20 m panchromatic (pan) and 10 & 20 m multispectral (ms), is a key asset for applications such as medium-scale mapping (at 1:25,000 and 1:10,000 locally).

2.2.1 Low Resolution.

In 1998, NOAA launched AVHRR3 which has a resolution of 1.09 km. This was enhanced when NOAA 19 was launched in 2009. Previous to that, its AVHRR satellites gave an imagery of one to eight km. Even with its improved resolution the infrared radiation maps may be the first stage in (woody) biomass assessment or provide a general overview of land use types. It is relatively inexpensive and, as with most satellite imagery, is repeatable so that time sequential data are available. These factors make AVHRR a valuable tool not only as a first stage for land use and biomass assessment, but for monitoring macro and seasonal changes in the biomass resource base.

As with information from other satellites (Landsat series and SPOT), the data are provided either as optical or digital products, the latter coming in the form of computer compatible tapes (CCT). In many case these tapes, with digital image processing systems, can be processed digitally to maximize the amount of information extracted from them.

The AVHRR data are used to identify and map vegetation/biomass classes by means of a Global Vegetation Index (GVI). By manipulating the data, an index of vegetation status can be calculated for each ground resolution element. It is called the Normalized Difference Vegetation Index (NDVI). Such data have been used for large area vegetation mapping.

For example, AVHRR 8 km imagery was used to map vegetation types/biomass types for African countries south of the Sahara – SSA - (ESMAP/World Bank. 1991). To assist with the identification of vegetation types that were determined by NDVI, field visits were made to the various regions involved. However, the ground truthing undertaken was very limited in relation to the overall area concerned. The principal purpose was to resolve the identification of transition zones. The important point is that ground truthing must be undertaken.

A detailed literature review for the SSA counties provided some limited data on the standing quantity of woody biomass and the annual increment that could be expected, thus giving an indication of yield potential for vegetation types. This was done by interlinking the biomass data base and the geographical information system (GIS) that was established from the satellite mapping data. However, the data base was seriously lacking. Some information was available for 'forest' types that are commercially exploited for timber, but these data only referred to merchantable (stem) volume. Little, if any, information was available for the remainder of the woody biomass in 'forests' and for bushland and woodland types there was a real data paucity, with only a limited information from research work. Thus, the lack of information made compilation of a standardized data base difficult. To improve accuracy, sufficient ground measurements in all vegetation types of total above-ground biomass are important.

To illustrate this point, the above SSA assessment for Ethiopia (excluding Eritrea) estimated the 1991 standing stock of woody biomass at 435 million dry tonnes, with an annual yield of 39 million t. A detailed inventory using Landsat TM and intensive ground truthing on all land types in 2001 to 2003, gave a woody biomass figure of 1,200 million t with an annual yield of 57 million t, including an estimate for Addis Ababa region (WBISP 2004). This excluded the stock of dead wood, (5.7 mill. t) and wood from agricultural clearing (2 mill. t), plus 11.5 million t from branches, leaves and twigs (BLT) that fall to the ground each year. Thus, the yield including dead wood, agricultural clearing wood and BLT is nearly 75 million t. The estimated demand for all wood products was 51 million t of which wood for fuel was 44 million t. There is a 2.8 times more growing stock and 1.9 times more yield from this inventory compared to the SSA survey when more accurate mapping and inventory data are used.

2.2.2 Higher Resolution.

The next more intensive stage of biomass assessment is to use satellite imagery with relatively higher spatial resolution for limited areas, for example a large country or selected vegetation types in a region such as the Sahel. Landsat Multi-Spectral Scanner (MSS) imagery has a resolution of 80 m and Landsat Thematic Mapper (TM) has a resolution of 30 m and Landsat Enhanced Thematic Mapper (ETM), launched in 1999 after Landsat 6 failed, has resolutions of 30 m for multispectral (ms) and 15 m for panchromatic (pan).

Apart from aerial photographs, the highest resolution is from SPOT imagery. Until SPOT 5 satellite was launched in May 2002, SPOT 4 has a resolution of 10 m for ms imagery and 20 m for pan. Compared to its predecessors, SPOT-5 offers greatly enhanced capabilities, which provide additional cost-effective imaging solutions. Thanks to SPOT-5's improved 5-metre and 2.5-metre resolution and wide imaging swath, which covers 60 x 60 km or 60 km x 120 km in twin-instrument mode, the SPOT-5 satellite provides an ideal balance between high resolution and wide-area coverage. The coverage offered by SPOT-5, namely 2.5, 5, 10 & 20 m pan and 10 & 20 m ms, is a key asset for applications such as medium-scale mapping (at 1:25,000 and 1:10,000 locally). A greater degree of ground truthing is required to identify vegetation or ground cover types than that is discernable through the lower resolution imagery. This may take the form of field work plus aerial reconnaissance or aerial photos/video sampling or a combination of the above.

A further multi-staged staged approach may be desirable, increasing accuracy with increasing resolution and ground verification, while at the same time, narrowing the area of investigation from a regional to a local level.

Maps of 1:500,000 to 1:1,000,000 would be drawn for the regional or national level or possibly 1:25,000 for small countries. Where greater details are required, say for a project, maps of 1:10,000 could be used.

AVHRR 1 km or Landsat MSS data could be used regionally or nationally, the scale chosen must be one that considers both the practical capabilities and the cost. Large scale mapping of sizeable areas requires considerable cartographical capabilities and time. A cost efficient alternative is the production of imagery maps that may be registered to existing national map grids. Stratification and sampling in phases from intense to moderate could be considered.

The use of higher resolution imagery such as Landsat TM/ETM or SPOT may be valid for annual monitoring of land use, land use changes and crop composition, as more reliable interpretation of ground cover/vegetation types is possible with the visible spectrum. Care should be taken that the imagery used is for the same season, as leafless periods or when both arable crops and trees have green leaves, could confuse the interpretation. Aerial photography may be the best means for annual monitoring, but cost would limit it to selected areas. For very large areas, a cost efficient method for monitoring ground cover changes could be to stratify the area on a broad climatic/ecological basis and randomly select a sample of imagery frames locations for which imagery would be obtained over the same period.

Before higher resolution imagery is used over a broad geographical area, it is useful to undertake a pilot study to determine: the amount of ground verification required; the interpretation methodology – visual, digital or a combination; the optimum period(s) for registration of imagery data to distinguish ground cover types; and the degree of stratification of ground cover types possible with digital image processing systems.

2.2.3 Mapping.

Ground cover/biomass type paper maps may be produced from the range of imagery and photography discussed above. The objective is to use such imagery to produce maps both to determine the spatial extent of the various land use types and to enable the biomass types to be stratified so as to facilitate subsequent ground truthing, or possible aerial assessment of biomass, especially woody biomass.

For AVHRR imagery with derived NDVI values, the identification and mapping ground cover/biomass types is based on interpretation and digital data. For Landsat MSS, TM and ETM imagery, digital interpretation is also used, although visual interpretation was used up to 1982. With the higher resolution SPOT imagery, both digital and visual interpretations are used. For all satellite imagery, generally the interpretation and mapping goes through three phases:

1. Data inspection and pre-processing; initial image interpretation and provisional biomass class mapping.
2. Field verification of provisional biomass class/type maps.
3. Final classification of biomass classes, especially woody biomass and the production of biomass type maps.

The NDVI data provided by NASA comes for regular time periods (daily, 10 days or monthly). The data should be registered to each other and errors/omissions corrected or cloud filtered out from affected pixels, - the smallest area that can be resolved on the imagery. This may not give a complete coverage, for large areas of persistent clouds may not be eliminated entirely. In that case aerial photographs may be a stand-by.

NDVI data for a given series of time periods, e.g. monthly, are then used for the initial interpretation in which provisional ground cover/biomass types are identified and mapped. An image with mean annual NDVI values may be created. This image provides a good indication of the amount and variation in annual vegetation productivity. Types or classes, made up of pixels with a statistical similar range, are grouped together.

The images formed from this provisional interpretation would be colour coded and hard copies obtained for field checking. The map scale may range from 1:50,000 for regional maps from 8 km AVHRR imagery to 1:1,000,000 for sub-regional or national maps using 1 km AVHRR imagery.

With Landsat or SPOT imagery, the acquired data would be evaluated, particularly for the degree of cloud cover. Radiometric calibration is applied to give a suitable range of colours for the data spectrum. Vegetation indices may be established on a temporal or one-shot basis using reflections in the infra-red and near-red spectrum. Paper copies of scenes at a scale of 1:10,000 to 1:100,000, (Landsat ETM & SPOT) 1:250,000, 1:500,000 and 1:1,000,000 (Landsat MSS) may be produced for field verification. Provisional land typing may be done using training sites for which ground cover information is known and overlays produced with this classification. However, in many instances paper copies of scenes are used for field verification without provisional typing.

Field verification is an essential element to the ground cover/biomass typing process, and up to a point, where sufficient sites have been observed, to ensure reliable typing. The greater the amount of verification, the more accurate would be the typing per se. For continental or multi-regional mapping using AVHRR data, only limited verification is usually possible in relation to the area covered and the land-use types involved.

As the area involved decreases, and grater interpretation accuracy is required, more detailed verification is necessary. The verification intensity will depend on the number and complexity of ground cover types. The usual method of ground verification is to take provisional ground cover type maps or paper copies or quadrants of image scenes, possibly with provisional typing done on transparent overlays. Using local maps or infrastructural information on the higher resolution imagery, field verification sites or transects would be identified that will assist in the verification ground cover types. For aerial photography, less ground verification may be necessary than with imagery as stereoscopic examination may more easily identify types; this is particularly so if large-scale photographs are used.

To establish accurately the coordinates of a ground verification site, the Global Positioning System (GPS) should be used. With the GPS, one can sight two or three satellites with the latter giving a three dimensional reading that includes altitude.

Where ground access is difficult, for example in large woodland tracts with little or no road access, aerial verification may be used in helicopters if available, or with small fixed winged aircraft. Apart from visual observations, this could take the form of low-level photos at identified locations or a video taken over a pre-set course between two identifiable points. A photographic record is then available of the ground cover types for later comparative reference or as training sites for confirming type identification. Also, photos may be taken of various biomass types during ground surveys, but being ground shots they are not as good as vertical ones for future comparative identification of ground cover types.

Final ground cover/biomass type maps may be produced using the provisional maps or paper image scenes and information obtained from the ground and/or aerial verification. Classification of the ground cover/biomass types may be done digitally (particularly with AVHRR and Landsat MSS imagery data) or manually (Landsat ETM and SPOT imagery or aerial photos). For digital classification, the values of each pixel in each spectral channel are compared to various sets of pixel values (training statistics) for areas of known classification (training sites), from local knowledge or field verification and interpretation. Algorithms or formulas can be used to then assign pixels and thereby areas on a map, to a given type. These types may be colour-coded, for easier visual interpretation on a digitally produced map.

The resultant ground cover/biomass types should be verified. This may be done by expert knowledge of the types being mapped. It may be done using ground information points that were reserved when the original interpretation was done. With coarse resolution imagery, such as AVHRR, there may be greater problems with interpretation that are often exacerbated by the low level of ground vegetation over wide areas. This is particularly so with variations in land use that may occur at a scale too fine for accurate interpretation. For example, small agricultural incursions into forest areas or the felling of tress in small areas for charcoal production. This is only noticeable when the scale of operation is increased, but it can be detected with Landsat ETM and SPOT imagery or aerial photographs. From experience in Africa, interpretation may be difficult in areas of steep slopes and high altitude. In Ethiopia, for example, there exist small areas with different biomass levels and NDVI profiles. Altitude was introduced into the classification procedure and contour lines digitised and placed on the classified image. With the exception of the montane forest type, all types occurring between 2000 and 3399 m in the area were merged to form a Highland Cultivation mosaic and those above 3400 m were merged to form an Ethiopian Montane Steppe (ESMAP/World Bank 1991).

Once the ground cover/biomass types have been satisfactorily established on a digital map, this can be used directly to print paper copies, generally at a very small scale for large areas. Enlargements may be made from these maps and larger scale sub-divisions of the digital map inscribed with numbers or in colour.

Classification done manually will use training sites where ground cover/biomass types have been interpreted through local knowledge or field verification. Areas of similar tones and textures may then be interpreted allowing for any local knowledge that may alter the interpretation. Mapping of the various types and other ground features, such as towns and roads may be done on transparent overlays on the thematic maps produced from the imagery. These maps should be registered to local maps of the same scale, e.g. 1:50,000 topographic map sheets and a mosaic made to compensate for the deviation of the imagery flight path from the north-south axis as used by the local maps.

Without good and up-to-date land use maps, it is difficult to estimate biomass stock and growth and changes in vegetation types over time, which of course will affect biomass stock. Governments need to know such information so that they can plan for sustainable use of biomass on a district basis.

FAO have recognized the importance of monitoring forest areas and is carrying out a remote sensing survey of the world's forests (FAO 2011). Its aim is to substantially improve the knowledge of changes in tree cover and land use over time. FAO states that "The increasing importance of climate change is also driving the push for better information because forests and related land use changes are estimated to be responsible for approximately 17% of human induced carbon emissions (IPCC 2007). Satellite data enable consistent information to be collected globally, which can be analysed in the same way for different points of time to derive better estimates of change. Remote sensing does not replace the need for good field data, but combining both provides better results than either method alone".

FAO further states that "The key outcomes of the Forest Resource Assessment [FRA] Remote Sensing Survey (FAO 2010b) will be to provide:

1. Improve knowledge on land cover and land use changes related to forests, especially deforestation, afforestation and natural expansion of forests.
2. Information on the rate of change between 1990 and 2005 at global, biome and regional levels.
3. A global framework and method for monitoring forest change.
4. Easy access to satellite imagery through an internet-based data portal.
5. Enhanced capacity in many countries for monitoring, assessing and reporting on forest area and forest areas change."

Landsat imagery for 1990, 2000 and 2005 was used on about 9,000 sample area of 10 by 10 km outside deserts and permanent ice. This is about 0.9% of the world's non-desert/ice land area. Initial results were released in a side-event to the 11th Conference of parties of the UN Framework Convention on Climate Change (UNFCCC), held in Durban, South Africa. An eight (8) page document of the initial results of the remote sensing survey has been released. Further information is available at: www.fao.org/forestry/fra/remotesensingsurvey/en. (FAO. 2011).

Of course, the FAO survey may exclude most 'trees' outside the forests, especially farm trees, which are usually more intensively managed. Also, their numbers tend to increase as forest areas decrease. The results may alert counties as to the over-all land-use changes, but the survey is 'large scale' and cannot detect what is happening to detailed land use changes in regions, districts or small areas. Such information is needed by counties, local bodies and projects. Since the concern about global warming, there are many initiatives to try to halt deforestation through tree planting and forest management etc. These include, the Clean Development Mechanism (CDM) under the UNFCCC, the Global Environmental Fund (GEF), Reduction in Deforestation and Degradation (REDD+) plus other bilateral, multilateral and local initiatives. For all these initiatives, maps are required and biomass resources need to be monitored over time: hence the importance of accurate and detailed information.

The author undertook a biomass assessment in Malawi in 1966/67 using a 1993 land cover map with a scale of 1:250,000. Landsat TM images were used from 1990-1991 and ground truthing was undertaken in May-October 1992. Biomass assessments were undertaken for the whole country, with emphasis on the catchments of the three main urban areas in the north, centre and south (Openshaw, K, 1997a & b). A repeat assessment was undertaken by the author in 2009 (BEST 2009). Unfortunately, there has been no update to the land-use map, but there has been a considerable change in land use, principally from forestry to agriculture. This has been driven by a population increase of over 40% from 9.2 million in 1996 to 13 million in 2008. Without current maps, changes in land use had to be estimated by assuming that the increased population had to clear forests to meet their food requirements. While this is a reasonable assumption, the government planners would be more convinced if land use changes could be demonstrated to them with good vegetation cover maps. However, Malawi does not have the trained personnel nor it seems the political will to finance land use maps on a continuing basis. Perhaps this is where donors could step in.

Providing accurate maps is an essential and first stage in biomass assessment. Table 2.1 shows a schematic diagram in the various stages in biomass assessment.

Table 2.1 Multi-stage approach to biomass assessment.

REVIEW OF EXISTING DATA & MAPS FOR THE AREA
|
LOW SPATIAL RESOLUTION IMAGERY
Large country or multi-country region
Supported by limited ground truthing and existing biomass data
Gives maps (1:5,000,000) with broad vegetation types and rough biomass estimates
|
HIGHER SPATAIL RESOLUTION SATELLITE IMAGERY
Small country or part of a country
Supported by ground truthing, and perhaps aerial photos, airborne videos
Plus existing data on biomass estimates
Gives maps or overlays (1:250,000 to0 1:1,000,000 with more reliable vegetation types and rough biomass estimates
|
BIOMASS RECONNAISSANCE INVENTORY
High spatial intensity: Landsat ETM+, SPOT
Intensive estimation of biomass for catchment areas, projects etc.
Low intensity inventory, perhaps with sub-plots for vegetation types
Supported by cartographic or imagery maps
Establish regressions and correlations between measurable parameters and biomass
Destructive sampling to establish regressions
May include non-forest as well as forest areas
|
BIOMASS MANAGEMENT INVENTORY
High spatial intensity: Landsat ETM+ 15 m (pan), SPOT
High intensity inventory, with sub-plots supported by maps in all areas
|
CONVERSION OF INFORMATION TO TOTAL ABOVE GROUND BIOMASS
Supported by maps and/or aerial photos
Establish regressions between various parameters
Divide into woody and non-woody biomass on a district/catchment area basis etc.
For woody biomass, estimate annual growth
|
COMPARE ESTIMATED SUPPLY TO DEMAND (PRESENT AND FUTURE)
ESTIMATE THE TOTAL STOCK OF CARBON IN WOOD ETC.
MONITOR ACCUMULATION/DEPLETION OF WOOD OVER TIME
TRACK LAND USE CHANGES OVER TIME
|

Source. Ryan, P.A. Openshaw, K. (1991).

3. Biomass measurements.

Biomass measurements are required for a number of purposes. For a country assessment of biomass availability, a complete picture of all types of biomass is required. For food, yields from different crops, both for the subsistence and commercial sectors are needed for planning purposes as is the growing stock and yields from various tree and forest formations. Likewise, when assessing carbon sequestration in biomass, especially woody biomass, both above and below-ground measurements are required. These are not one-off measurements, because the quantity and quality of land use changes have to be continually monitored if meaningful interventions are to be proposed and executed. There are several donor biomass projects where it is mandatory to report progress and for this, up-to-date maps and biomass stock are essential. In developing countries, the use of wood for fuel is dominant and therefore, because fuelwood is required near to demand centres, assessments have to be local: this also applies to crop residues and dung. On the other hand in developed countries, where the principal demands for wood are for sawnwood, board products and paper, supply estimates at a regional level may be sufficient.

Associate measurements may be necessary such as the amount of carbon in soils. Generally, there is a greater accumulation of carbon in forests soils than in grassland and arable soils on the same geological soil types. This is important when estimating carbon stock on the various land use types.

The degree of importance of the various biomass types should determine the intensity of measurements. For example, if crop residues and dung are an important energy source, as in many rural areas of south-east Asia, then more accurate information is necessary than in areas where they are seldom used, except for lighting fires or after harvest. The different types of biomass measurements will be described, starting with non-woody biomass.

3.1 Biomass measurement of annual and short rotation crops.

Usually, non-woody plants have life cycles not more than four to eighteen months. Their biomass 'waste' can be collected, but must be used within a short time period, otherwise it will decompose. The collection site is generally the field, but it may be at factories or milling facilities. From an energy standpoint, the annual production is the potential available energy, but there are other uses for this biomass such as animal feed, a soil conditioner, thatching, weaving, construction and paper making etc.

These residues are renewable, unlike woody biomass, which is conditionally renewable, conditional on the average off-take of wood being no more than annual growth. However, annual crop production depends on climatic and soil fertility factors, therefore, it is not constant. Also, when counting availability figures, it is important to avoid double counting. If resides and grasses are used for animal feed, they should not be counted as potential energy sources, although the dung production is.

The division between woody and non-woody plants is not clear cut, cassava and cotton stems are woody, but because they are agricultural crops, it is easier to treat them as non-woody plants. On the other hand, coffee husks are treated as residues, but coffee bush clippings and stems are regarded as wood, as is bamboo. What is important is the kind of agricultural crops and residues that are generally available and suitable for fuel etc. rather than what is the total non-woody biomass production at given sites or areas. When measuring non-wood biomass, a distinction should be made of residues that are in the field, at the house or that are processed waste at the factory or milling facility. This is because, the further away it is from the consumption centre, the less it will be used. Also, some crop residues are left standing while others are cut, the latter being more easy to collect. Table 3.1 gives examples of the various types of non-woody biomass at different locations. Several cropping patterns are not single species, especially in developing countries. Some fields may have maize and beans planted together or there may be a seasonal change from maize to cassava. Where crops such as cotton is grown, the stem and roots should be removed and either burnt in the field or used for energy purposes because of nematode problems. Also, cotton and tobacco are 'demanding crops' in terms of mineral requirements and thus, they should be grown in rotation with other crops, preferably nitrogen-fixing crops. Therefore, it is important to understand the farming systems when interpreting remote sensing imagery.

From each of the categories, measurements can be taken and related to the food or fibre part of the plant. Of course there are different varieties of the same species with different yield characteristics. Rice is a typical example with deep water, upland, high yielding, traditional and glutinous etc. If rice is an important fuel and there is significant difference in residue yields between varieties, then detailed measurements should be undertaken. On the other hand, if a particular crop is only a marginal fuel then superficial measurements may suffice.

Most crop residues have a variety of uses, some of which have higher economic and ecological values compared to fuel, thus the percentage available for the different uses should be estimated. Where food, fibres and beverages are processed at a factory or a grain milling facility, there are processed wastes which can be and are used as fuels, bagasse in sugar factories being a good example. Again molasses could be used to produce motor (ethanol) fuel.

The amount of above-ground plant biomass is usually one to three times the weight of the actual crop itself. Estimated have been made of these residues for various crops and Table 3.2 gives a summary of them

Government statistics could provide crop yield figures or they may be obtained for example from FAO's Annual Yearbooks of Agricultural Production. However, it must be pointed out that in order to obtain accurate estimates of residue production and crop yield, field measurements should be made not only of residue and crop production, but also of the uses of residues. Satellite imagery could be used to assess the areas of specific crops and residues given adequate ground verification. This could be checked against data from other sources. Cost of residue assessment can vary from about $500 to $10,000 depending on requirements. If just a country wide estimate is required to make a complete assessment of biomass supply, knowing that crop residues are not an important fuel, then consulting crop production statistics by areas or region may only cost in the region of $500 to give a broad overall picture of residues production. On the other hand, if residues are an important source of energy, as for example in South Asia, then detailed assessment including field sampling may cost in the region of $5,000 to $10,000 or more, depending on the degree of information that is required, such as the actual and competing uses of these residues.

Table 3.1 Types of non-woody biomass from different crops at various sites.

Crop	Field (standing)	Field (cut)	House	Factory
A. Subsistence/cash				
Cereals				
Maize	Stover and leaves	Cob, leaves	Cob	Parchment
Deep water paddy	Tough straw - nara	Tender straw - kher	Kher	Husk
Normal rice paddy	Stubble	Straw	Straw	Husk
Millet, sorghum	Straw	-	Chaff	-
Wheat etc.	Stubble	Straw	Straw	Husk/bran
Cassava	-	Stem	-	Waste
Papyrus	Stem	-	-	-
Plantain, banana	-	Stem	Fruit stem	
Pulses	Stem	-	-	-
Heather etc.	Whole plant[1]	-	-	-
B. Cash crops				
Coffee (dry process)	(woody biomass)	(woody biomass)	Cherries[2]	Parchment; husk
Coffee (wet process)	(woody biomass)	(woody biomass)	-	Cherries; husk
Tea	(woody biomass)	(woody biomass)	-	-
Cotton	-	Roots and stems[3]	-	(tow)
Coconut, Palm nut	(wood)	Fronds	Husk; shell	Husk; shell
Groundnut	-	Stem	Shell	Shell
Jute, Kenaf, Flax	-	Waste	-	Waste
Nut trees	(woody biomass)	(woody biomass)	Shell	Shell
Pineapple	-	Old plants	-	Waste
Sugar cane	-	Leaves	Stem	Bagasse
Sugar beet	-	-	-	Waste
Sisal	-	Old plants	-	Waste
Tobacco	Stem	-	-	Sweepings
C. Indirect use				
Grasses[4]	(grass)	Hay/silage	Old thatch	-

1. In some countries e.g. Lesotho, heather type plants are uprooted and burnt. 2. Coffee cherries make good fertilisers. 3. Cotton stems are uprooted/burnt because of nematodes. 4. Grasses mainly used as animal feed, a by-product is dung.
Source. Ryan, P.A. Openshaw, K. (1991).

Table 3.2. Ratio of crop to residue production for specific crops. (Unit: air dry tonne for residue and crops)

Crop	Residue	Ratio	Residue	Ratio	Residue	Ratio
Maize: Stover and leaves		1.0 – 2.5	Cob	0.2 – 0.5	Husk	0.2
Deep water rice: Straw		2.0 - 5.0	Bran	0.1	Husk	0.2
Rice	Straw	1.1 - 2.9	Bran	0.1	Husk	0.2
Millet	Stalk	2.0 – 3.7				
Sorghum	Stalk	0.9 – 4.6				
Wheat	Straw	0.7 – 1.8				
Barley	Straw	0.6 – 1.8				
Rye	Straw	1.0 – 2.0				
Oats	Straw	0.9 – 1.8				
Cassava	Stem	0.2				
Cow pea	Stalk	2.9				
Pigeon pea	Stalk	5.0				
Coffee (wet process)			Cherry	0.75	Husk	0.25
Coffee (dry process)			Cherry and husk			1.0
Cotton	Stem	3.5 – 4.0				
Coconut	Frond	5.0	Shell	0.65	Husk	1.60
Ground nuts	Straw	2.3 – 2.9	Shell	0.5		
Sugar cane	Bagasse	0.1 – 0.3				
Sugar beat	Pulp	0.1 – 0.2				
Sisal	Waste	1.2				
Sesame	Stalk	3.0 – 5.0				
Jute/Tobacco	Stick/stalk	2.0-3.0				
Papyrus (sustained production)			10 – 15 air-dry t/ha/yr			

Source. Ryan, P. Openshaw, K. (1991).

The ash content in residues varies considerably. Rice straw has about 19% ash, whereas coconut shells have about 1% ash. If residues are going to be used for energy, then the ash content affects the energy value of the residue. Dry residues with 1% ash have an energy value of an estimated 17.4 MJ/kg (MegaJoules per kilo) whereas with 19% ash the energy value is 14.3 MJ/kg. The moisture content of residues also affects its energy value, the drier the fuel, the more energy it has per unit weight and the less energy is required to drive off this moisture. Thus, with 15% moisture (wet basis) and 19% ash, the energy value of rice straw will be 12.0 MJ/kg whereas with 40% moisture its energy value will be 9.4 MJ/kg. Again, the drier the residue, the more complete combustion is obtained.

The ash contents of various residues and their energy values can be obtained from various publications with a search of the World Wide Web: similarly for energy values.

3.2 Animal residues (dung).

Like crop residues, dung is not an important fuel in many countries and therefore, not much time should be spent on measuring it. However, in certain countries, notably those in the Indian sub-continent and in one or two areas in Africa, dung is one of the primary household fuels. In Lesotho for example, dung produced in different localities is given different names; the most prized for fuel is that which is compacted in the animal enclosure next to the house. While dung cakes are the most common fuel in India when wood is scarce, there are millions of biogas digester in India and many other countries, especially China, where methane is produced from the anaerobic fermentation of animal (and plant) wastes, with the remaining slurry being an excellent fertilizer. Also, with the upsurge of 'factory' farming in many countries, the disposal of animal waste has become a problem, and the production of biogas may be an opportunity to turn the waste into a renewable energy source. Again, the waste can be burnt directly as an 'industrial' energy source.

One positive aspect of dung is that it is renewable and produced daily. But when assessing potential supply, it is important to determine accessibility. Furthermore, dung may be purposely left in the field as a natural fertiliser. Dung production is proportional to food intake, which is more or less related to the animal's size and weight. Table 3.3 gives an estimate of dung production for various animals per 500 kg of live weight.

Table 3.3. Daily dung production per 500 kg of animals live weight.

Animal type	Dung production per 500 kg of animals		Estimated No. of animals per 500 kg in Kenya
	Wet weight (kg)	Air-dry wt. 13 % mc wb	
Dairy cattle	38.5	3.8	3.85
Beef cattle	41.7	4.9	2.75
Swine	28.4	2.7	10
Sheep/goats	20.0	5.0	20
Poultry	31.3	7.8	150
Horses	28.0	4.9	3.20
Donkeys	28.0	4.9	3.33
Camels	28.0	4.9	1.29

Note. mcwb = moisture contend wet basis (wet weight – dry weight/wet weight).
Source. Methane Generation. US National Academy of Science (1981) adapted.

Dung has several other uses besides energy, the principal use being manure, but it is also used as a binding agent when constructing simple houses etc. For a quick country assessment of energy resources to give a complete picture, an estimate can be made based on animal numbers, by type, using factors for their daily production of dung. Where dung is an important fuel, more detailed measurements should be made of important animal species by specific areas over time. Assessment costs can vary from about $500 to $5,000 or more, depending on its importance.

The ash content of dung is much higher than that of plants at the same moisture content, because many mineral in plant food, especially carbon, are not absorbed by the animals but excreted in a concentrated form. On average the ash content of dung is between 23% and 27% with a 13% mcwb and this affects its energy content. Dung with a 25% ash content and 13% moisture has an energy value of about 15.2 MJ/kg. If dung is passed through a digester, the resulting biogas will have about 60% methane with an energy value of about 21.5 MJ/m^3, (30.1 MJ/kg), whereas pure methane has an energy value of 35.8 MJ/m^3 (50.1 MJ/kg).

3.3 Biomass assessment of perennial crops.

Assessing biomass in perennial crops is more difficult than annual crops because such crops build up a store of woody tissue over time and unless the crops are even-aged, there is a whole range of age-classes in the area, district, region or country. There are different types of biomass crops ranging from closed forests to open woodlands to shrubland and bushland. There are isolated trees or clumps scattered on farmland. There are trees on short rotations (2-10 years) to forest stands well over 100 years and the list goes on. The land use maps from aerial photos and/or satellite imagery will give a breakdown of the area and forest types, including bushland and shrubland, plus arable and pastoral areas etc.

If only a general estimate of woody biomass is needed, then existing information of stock by vegetation type can be used to generate country or regional estimates, as was done in the woody biomass survey for Sub-Saharan Africa (ESMAP/World Bank 1991). However, there was a dearth of ground measurements and so the estimated only had a low accuracy. This was illustrated when a detailed inventory was done for Ethiopia in 2003: this gave a growing stock estimate 2.8 times larger than that in the earlier SSA survey.

Brown and Lugo (*Science 1984*) have made some correlations between total wood and stemwood in tropical forests and the author was in charge of an inventory in Benin in 2000, when sample plots were felled and correlations established between stem wood and total above-ground wood biomass, both alive and dead. (PGFTR, 2000). In Benin, the following relationships were established for above ground wood: Table 3.4.

Table 3.4 Estimation of above ground (and below) ground biomass volume and weight.

		Above ground volume and weight (above 15 cm. girth) Average volume or dry weight per ha.				Small trees/ Shrub	All wood
		Stem volume total m^3	Branch volume total m^3	Stem + branch volume m^3	Stem + branch weight t.	total weight <15 cm. t	total weight t.
Live wood							
Average	m^3/t ha.	19.4	11.2	30.5	21.7	0.9	22.5
Dead wood							
Average	m^3/t ha.	1.3	0.1	1.4	1.0	1.6	2.6
Live and dead wood volume & weight							
	.	m^3	m^3	m^3	t.	t.	t.
Average	m^3/t ha.	20.6	11.3	31.9	22.6	2.5	25.1
% dead wood		6	1	4	4	65	10
Live and dead wood weight							
		Stem	Branch	Stem + branch	Small trees	Total	(Roots)
	t/ha	14.65	8.00	22.65	2.48	21.13	(11.08)
percentage		58	32	90	10	100	
% live stem wood		100	57	62	18	80	(85)
% of stem wood		100	54		17	71	(76)

Note. Figures may not add due to rounding.
Source. PGFTR. (2000).

Today, estimates from Benin and the Ethiopian inventory plus inventories in several other countries throughout the world, could be used to build up more reliable estimates by various 'forest' types. However, where accurate estimates are required, ground inventories of woody vegetation in all areas are needed, using the maps and/or imagery to stratify the strata, to give a cost effective assessment to a desired level of accuracy. Regressions are established between measurable parameters and biomass to utilisation limits with field and/or aerial sampling being undertaken to a specified intensity to achieve a given standard error. Considerable work has been done on making correlations between merchantable roundwood and total tree volume in homogeneous coniferous stands in the U.S.A. and Canada (Hitchcock, H.C. McDonald, J.P. 1979), but little work has been done on similar regression analysis for trees in more heterogeneous tropical and sub-tropical forests and woodlands.

Many traditional forest inventories only measure live stem wood and in some instances only stem wood of 'commercial' trees. If this is taken as the measure of total above ground biomass, then 45 % of the total volume or weight would have been neglected, including 10% of dead wood, in the case of the Benin inventory.

The above inventory was on all land use types in a specific project area, some of which was arable or pastoral land. Also, there is a range of age classes represented, therefore on average the volume/mass at maturity will be double that shown in Table 3.4, namely 42 t/ha or about 60 m^3/ha of above ground woody biomass. This latter figure is the one used when estimating the annual yield, if no field measurements are available. Therefore, when estimating the annual yield of woody biomass for any one vegetation type, one should double the estimated growing stock for the population and then divide by the nominal rotation age. For example, if the estimated total above ground growing stock in a forest is 160 m^3/ha and the estimated rotation age is 80 years, then the annual yield will be at least 4 m^3/ha, not 2 m^3/ha. This is a common mistake that is made. Again it must be remembered that in most sample plots, wood that has been removed is not considered and therefore, even this yield estimate may be lower than the actual yield.

This can be illustrated by using yield estimates from the British Forestry Commission's Management Tables for Douglas fir (*Pseudotsuga menziesii)* (HMSO 1971). The rotation of yield class '24' is 50 years, at which age the total stem volume production is 1,200 m^3, of which, the main crop to 7cm top diameter is 574 m^3. At age 25, the standing stock is 225 m^3 and 229 m^3 have been removed as 'thinnings'. A sample from different age classes, may give an average volume of about 250 m^3/ha. If this figure is then divided by the rotation age of 50 years, the annual yield would be 5 m^3/ha. Even doubling this figure to obtain an estimate of the standing stock at the rotation age, would only give a yield of 10 m^3/ha, whereas, accounting for removals, the annual yield of stem wood is 24 m^3/ha! This is why estimates of annual yield are usually on the low side, especially if the average volume of a vegetation type is taken as the volume at maturity. Local people are always using forests to collect dead wood, cut poles and extract the occasional mature tree for timber as well as collecting non-forest wood products; therefore, the measurement of the standing stock does not represent the average total stock, even in so-called 'undisturbed' forests. This is why it is important to have permanent sample plots on the various vegetation types to monitor growth and removals as well as wood lying on the ground!

There are a limited number of correlations for African forests and woodlands by Chidumayo (1990), Stromgaard (1985) in Zambia and by Bird and Shepherd (1989) in Somalia, but more work is required in tropical countries to develop such correlations. Another publication, which gives sampling methods is a book entitled 'Measuring Trees and Forests' by M.S. Philip (CABI 1994). This book was written for students in Africa.

The general procedure to estimate total weight and/or volume of a tree to defined utilisation limits is a variation of the following:

1. Fell the tree at a good coppicing stump height (20-30 cm above ground) and separate into various components – poles, sawlogs, peeler logs, firewood logs, large braches, small branches, twigs and leaves.
2. Measure the length and top and bottom diameters or girths (or mid-diameter/girth) of all utilisable logs by species. For cordwood (stacked fuelwood) and poles stacked volume may be measured as well.
3. Weigh the components by sections, taking sub-samples of leaves from small branches to determine the weight of leaves per unit weight of branches.
4. Use a moisture content meter to determine the moisture content of each component, the moisture content of a small sample of wood can be verified in the laboratory using an oven.
5. Finally, sum the volumes and weights of the sections and components within the one or more utilisation limits.
6. This should be repeated for dead wood, small trees, shrubs and bushes, both dead and alive, in the sample plot.
7. Thus, total above-ground weight, including the relationship between the stem wood, the whole tree and the total biomass on the area can be established.

Trees outside the forest, especially farm trees are an important source of wood and non-wood products: they are usually intensively managed. Therefore, it is important to measure the stock of such trees. A stratified random sample can be used after the analysis of the land use maps produced from remote sensing. More details of measuring trees outside the forest are in the World Bank Energy Series paper # 48 (Ryan, P.A. Openshaw, K. 1991). Also there should be (local) demand surveys of biomass use, which would endeavour to find out consumption of wood by type and the sources of wood by percentage etc.

When the author was in charge of a 'farm' tree survey in Kenya, eleven farm types were recognised and sample surveys were undertaken in each of these types. The survey consisted of recording all trees in a 10 m wide by 50 m long strips on a rectangular line of 3 km, thus teams measured 15 plots each day and the total number over two weeks was 180 plots for each of the 11 farm sites (99 ha). From this survey, it was found that nearly 10% of the farm area was covered with trees/shrubs with an average growing stock of 15 m^3/ha (11 t/ha). Because farm trees are intensively managed, a 15 year rotation was assumed. Thus, the estimated yield should be at least 2.0 m^3/ha (1.4 t/ha). This excluded coffee and tea areas, which were measured separately. They gave an estimated stock of 5.3 m^3/ha (3.8 t/ha) with an annual yield from prunings, cleared bushes and shade trees of 1.7 m^3/ha (1.2 t/ha). (Openshaw, K 1982). Thus, while the overall stock of wood in the farm areas is not very high, the annual yield of wood is important because it is easily accessible.

Similar estimates can be made for grasslands, transport networks and urban areas etc. In some countries, bushlands and shrublands may have to be assessed separately. In Kenya there is the Kenyan Rangeland Ecological Monitoring Unit (KREMU) which monitors such areas through permanent sample plots. These rangelands, mainly consisting of shrubs, bushes and small trees, cover 83% of the land - 47 million ha, with an estimated growing stock 600 million t/wood – 13 t/ha (18 m^3/ha), excluding dead wood. This gives an annual yield of about 0.9 t/ha (1.3 m^3/ha), but only about 33% is utilisable, the other 67% being too remote. However, this area contains about 450 million t of organic carbon in above and below-ground woody biomass and so it is an important store of carbon. (KREMU 1981).

In summary, remote sensing can give good estimates of vegetation categories by area. These can then be used to estimate biomass, especially woody biomass, on the various land use types. Stratified random samples can be generated according to the importance of each type and all above-ground woody biomass, both living and dead should be measured. Relationships should be established between measurable variables such as diameter at breast height (dbh) and tree height and total above-ground biomass. Separate measurements may have to be undertaken for small trees, bushes and shrubs and dead wood. Measuring annual growth, especially in tropical countries is more difficult, for many trees do not have annual rings. However, where there is just one rainy season per year, trees may have annual rings, thus taking core samples can be used to count the rings or they can be counted on felled trees. Where trees have been planted, there should be records of their ages, but permanent and temporary sample plots should be established to monitor growth over time, especially in tropical forests. In temperate forests, especially plantations, there may be good growth and yield records, including management tables.

Assessing below-ground woody biomass is more difficult to measure. Allometric analysis may be used to estimate below ground biomass in roots and rootlets. Allometery is the change in proportion with the size of the body or dimensional scaling. Roots have to support the above-ground weight of trees and underground roots spread according to branch dimensions and in dry areas, they also go in search of water. Where trees are closely spaced, roots give mutual support to the above-ground mass. Therefore, on average there is less individual root mass in closed tree formations than in open formations. Some studies have been made and allometric analysis applied to trees, especially fruit trees that have to support apples, pears, citrus fruit and avocado pears etc. As a rule of thumb, about 20% of the total tree weight is below ground in closed formations and 33% in open formations. Such information is important for measuring the store of carbon in woody biomass.

Measuring soil carbon may also be important when determining carbon sequestration on different land use types. Organic soil carbon accumulates through the death of roots and rootlets and from the decomposition of surface litter. From various research work (Bouwman, A. 1990; Cerri, C.C. and Volkoff, B. 1987), it has been determined that there is a build up of soil carbon from arable lands to forests in the same soil types, with grassland and woodland being intermediate between these two. A tropical forest may have twice as much soil carbon per unit area as does a similar arable area. Woodland and grassland may have about 50% more. Therefore, not only do trees accumulate organic carbon in their tissues, but they facilitate a build up of carbon in the underlying soil. The survey of biomass in Benin mentioned above, commissioned soil samples to be taken and analysed for soil carbon on the various land use types in the project area. The result showed an increasing accumulation of soil carbon from an arable baseline to a closed forest formation. These results were then used to calculate total above and below ground carbon stored in wood and soils. It was a baseline survey for a GEF sequestration project. (PGFTR, 2000).

3.4 Cost assessment for woody biomass.

Woody biomass assessment costs are rather specific for each assessment. Costs will vary for each specific case according to the following factors:

1. The amount of reliable data, including vegetation type maps, imagery and/or aerial photography and the existing woody biomass estimates for the area.
2. The spatial area to be covered by the assessment.
3. The assessment intensity as dictated by management and planning needs.
4. The quantity and value of vehicles and equipment to be acquired.
5. The amount of expatriate and/or local technical assistance required.
6. The kind of imagery needed and whether digital data and analysis is necessary.
7. The cost of salaries and allowances for expatriate and local staff.

Table 3.5 gives cost estimates for various remote sensing and ground truthing elements. The elements are divided into imagery costs, map production, ground verification, ground assessment and management assessment. Expertise in inventory work and statistical analysis is required as well as well trained field and analysis staff.

Table 3.5a. Cost Estimates for Woody Biomass Assessment with NOAA imagery. : US/km^2

NOAA Imagery			Air photos
Assessment elements	4-8 km resolution	1.09 resolution	
Basic imagery & digital data	$3.3x10^{-5}$	$7.0x10^{-5}$	10-12
Cartographic or image map production	0.054 - 0.122	0.054 - 0.122	2-3
Ground verification	0.027- 0.068	0.027 - 0.068	0.1- 0.2
Low intensity ground assessment	0.130 – 0.260	0.260 - 0.520	1.-4
Management assessment	-	0.050 – 0.100	4-10

Note. AVHRR = Advanced very high resolution radiometer.

Table3.5b. Cost Estimates for Woody Biomass Assessment with Landsat imagery.

Assessment elements	Landsat Imagery: $US/km²			
	MSS: 80 m	TM: 30 m	ETM+ 15 m pan	ETM+ 30 m ms
Basic imagery & digital data	0.007 - 0.012	0.014 - 0.020	0.020 – 0.003	0.006- 0.009
Cartographic or image map production	0.068 - 0.135	0.270- 0.675	0.270 - 0.675	
Ground verification	0.068 - 0.135	0.270 - 0.540	0.270 - 0.540	
Low intensity ground assessment	0.270 - 0.540	0.270 - 0.675	0.270 - 0.675	
Management assessment	0.675 - 2.700	1.350 - 5.400	1.350 - 5.400	

Note. AVHRR = Advanced very high resolution radiometer. MSS = Multi-spectral scanner. TM = Thematic mapper. ETM + Enhanced TM; pan = panchromatic; ms = multispectral.

Table 3.5c. Cost Estimates for Woody Biomass Assessment.

Assessment elements	2010 SPOT Imagery: $US/km²				
	2.5 m pan	5 m pan	10 m ms	10 m pan	20 m mws
Basic imagery & digital data	1.88- 2.81*	0.94– 1.88*	0.94	0.33 – 0.53	
Cartographic or image map production**	3.00 – 3.90				
Ground verification	0.68 – 1.08				
Low intensity ground assessment	1.35 – 5.40				
Management assessment	5.00 – 12.00				

Note. Pan = panchromatic; ms = multispectral. * = false colour ** Off-the-shelf.
Source. SPOT Image Corporation, 14595 Avion Parkway, Suite 500, Chantilly, VA 20151. USA. sales@spot.com
For all Tables 3.5. http://edcsns17.cr.usgs.gov/helpdocs/prices.html;
http://www.sarracrnia.com/astonomy/remotesensing/primer044.html

Tables 3.5a, b, & c show a range of cost estimates per km² for various elements in woody biomass assessment. The total cost may range from about $50 to $70 for a village catchment to about $3 million for urban catchments over a combined area of some 140,000 km². As a comparison, the cost estimated for 1990 are given in Table 3.6.

Table 3.6. 1990 Cost Estimates for Woody Biomass Assessment: $US/km²

Assessment elements	AVHRR (4-8 km resolution)	Landsat		SPOT: 10 ms; 20 pan	Air photos
		MSS: 80 m	TM: 30 m		
Basic imagery & digital data	0.01 -0.02	0.02- 0.05	0.1-0.15	1.0-1.5	8-10
Cartographic or image map production	0.04- 0.09	0.05-0.1	0.2- 0.5	1.5-2.0	2-3
Ground verification	0.02-0.05	0.05-0.1	0.2- 0.4	0.5-0.8	0.1- 0.2
Low intensity ground assessment	-	0.2-0.4	0.2-0.5	1.0-4.0	1.0-4.0
Management assessment	-	-	1.0- 4.0	4.0-10	4.0-10

Note. AVHRR = Advanced very high resolution radiometer. MSS = Multi-spectral scanner. TM = Thematic mapper.
Source. WB Energy Series Paper # 48. Ryan, P. Openshaw, K. (1991).

Costs of satellite imagery and maps have been declining over the last 20 years and free maps may be available from NOAA and NASA. Contracts could be made with the three agencies shown above and discounts may be available. Not mentioned is the Russian Satellite Communications Company base in Moscow, but with world-wide offices. They have competitive prices and information can be obtained at market@rscc.ru

Most woody biomass assessments require at least one person with expertise in forest mensuration and statistics and their application to total above-ground woody biomass assessment. Team leaders and field staff should be trained in the methodologies and monitoring involved. The equipment is not expensive and may be already available in forestry departments. Computer hardware and software should be available for recording and analysing the data and local laboratories should be used for soil carbon assessment etc.

4. **Discussion and Conclusions.**

Remote sensing is an important tool to assess vegetation types and land use changes. Without good maps it is impossible to assess biomass stock and yields on the various land use types and changes over time: remote sensing is a key element in preparing maps and monitoring land use changes. For annual crops it may be possible to assess yields, if the crop type can be distinguished or the crop variety in particular areas is known. Knowing this, the crop residues can be estimated both in the field and at the milling facility/factory etc. For some animal production, it may be possible to assess numbers from the carrying capacity of meadows and grasslands etc. But many farm animals are in part stall fed or raised in 'factory' farms. Therefore, an animal count by species is required together with an average weight per animal type, if an estimate of dung production is needed.

For perennial crops, it is difficult to estimate growing stock using remote sensing alone, although aerial photographs have been used in open formations. Each year, FAO compiles a report entitled 'the State of the World's Forests'. This gives forest areas, growing stock and carbon stock. However, FAO mainly relies on country report, many of which may be unreliable and in some cases data in missing (FAO 2010b). FAO have recognised this and is undertaking a remote sensing survey to be completed in 2011 (FAO 2010b). An interim report was published in November 2011 (FAO 2011).

However, this survey only gives a broad country picture of forest cover. Countries and projects within countries require more detailed assessments of land use types and woody biomass growing stock and yield. This is particularly so for carbon sequestration projects and reduction of deforestation and degradation projects. In such cases, specific areas have to be monitored for carbon accumulation and tree growth. Countries require information on a district or regional basis, so that meaningful interventions are planned. These may include, exploiting woody biomass in areas where surpluses occur and promoting tree planting (and conservation) in areas of shortage. But without reliable information, cost-effective interventions may not be achieved.

FAO has recently published a paper entitled "What Woodfuels can do to Mitigate Climate Change?" (FAO 2010c). One of its main points is that the 'modern' use of woodfuels can substitute for fossil fuels: for electricity generation; to provide heat and steam etc. for industry; for household use (cooking and heating); and as a feedstock for liquid fuels for motive power. However, the paper asserts that much traditional (household) use of wood energy is unsustainable and in order to reduce deforestation, there should be a shift away from such use. Of course, in areas of high population densities in developing countries, the trees in the catchment areas which supply wood products, especially fuel, may be being over-exploited. This is where detailed studies of supply and demand are required and remote sensing should be an integral part of these studies. But for tropical countries as a whole, the sustainable supply of wood is three to five-times demand, based on the standing stock of trees alone and not including dead wood, small wood and removals, (Openshaw, K. 2011). In fact, rather than curtailing the 'traditional' use of woodfuels, in many areas it could be expanded and used in place of fossil fuels. This is why it is necessary and important to undertake proper supply-side assessments.

There are many projects that are financed by bi- and multi-lateral donors as well as governments and NGOs based on curtailing deforestation and forest degradation or increasing the stock of wood through afforestation and reforestation. For such projects it is important to have good and accurate baseline surveys of existing ground cover, especially woody biomass. Remote sensing should be an important tool in providing information of the project area and the surrounding areas to monitor the land use changes, both positive and negative, that occurs because of the project. However, most deforestation is caused by population increase. If agricultural productivity does not at least keep pace with population increase, deforestation may continue despite the efforts to increase tree planting. Remote sensing is an excellent tool for this, for it could monitor agricultural areas for changes and also for the types and number of annual crops.

A survey was under by the author to examine the causes of deforestation in Sub-Saharan Africa over a 10-year period 1980-1990. The increase in population in each country was monitored and their food requirements were estimated using grain productivity per unit area in each country to give a measure of new arable land requirements. This was then compared to deforestation over the same time period. It was found that the demand for arable land accounted for more that 90% of deforestation and this did not take into account land required for pastoral agriculture and urbanisation. This is written up as Chapter 11 in a book entitled Climate Change and Africa. (Low. Pak Sum 2005). Yet today many people equate deforestation with the use of wood products. Many people treat removal of trees as deforestation, but not the removal of annual crops. In both cases it is harvesting of renewable resources! This is another important reason for assessing biomass on all land use types and monitoring it over time.

This article has detailed methods to undertake such assessments using a combination of remote sensing and ground truthing. They both complement each other.

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