DIPARTIMENTO DIBAF

DOTTORATO DI RICERCA IN

SCIENZE E TECNOLOGIE PER LA GESTIONE FORESTALE E AMBIENTALE

XXIII CICLO

ON THE EXTENSION OF LARGE-SCALE FOREST INVENTORIES TO NON-FOREST AREAS

(Settore scientifico-disciplinare: AGR/05)

TUTORS:

Prof. Piermaria Corona

Prof. Luigi Portoghesi

COORDINATORE:

Prof. Gianluca Piovesan

DOTTORANDA:

Dott.ssa Maria Vincenza Chiriacò

Anno Accademico 2010-2011

Index

1. Introduction

Trees outside Forests (TOF) refer to those trees found on lands not defined as “Forest” and “Other Wooded Land” as per FAO definitions and include all those trees grouped in small woodlots and tree rows, or those scattered trees, occurring outside that areas conventionally indicated as forests whether in urban, rural or agroforestry systems.

Trees outside forests represent a widespread and multi-purpose resource: they are frequently domesticated, cultivated or tended and offer a set of environmental services and products. It can be easily assumed that TOF have in principle similar functions as trees in forest, referring to environmental services such as carbon sequestration, erosion control, soil and water quality improvement, conservation of biodiversity as also with respect to timber and non-wood-forest products.

Several studies have demonstrated the multiple functions of TOF as the wood production, such as timber and fuelwood (Mezzalira, 1997a), the secondary non-wood production as bark, seeds and fodder for domestic animals and other edible products (fruits and honey) (Mezzalira, 1997b), the storage of atmospheric CO_2 (Schoeder, 1994; Lopez et al., 1999) and the consequent positive effects on climatic mitigation (Borin & Maccatrozzo, 2005), the hydro-geologic protection for soil and for water quality (Endreny, 2002), the mitigation of wind erosion and of the desertification process (Agrimi & Portoghesi, 2002), the protection for crops in favour of an higher productivity (INEA, 1999), the conservation of the animal and vegetal biodiversity (Bellefontaine et al., 2001) and of the cultural land heritage on traditional landscapes (Cullotta et al., 1999).

Trees outside forest are intimately linked to the society around them and the wealth and diversity of their uses and services create a permanent daily interaction with local people. The ancient society, as well as the modern one, exploited this resource. Sometimes TOF denote symbolic and cultural representations and their use is governed by local practices, customs and, in some case, by laws. This is a true for countries with scant forest resources as for those more richly endowed.

Tree resource conservation and expansion is a strategic issue in low forest cover countries (LFCCs), where trees outside forests - growing in rural or urban areas, in orchards, gardens, savannah or agroforestry parklands, as shade trees or permanent crops - constitute an essential source of wood and non-wood products, crucial for people's daily needs and for poverty alleviation. In this way TOF contribute significantly to local economies and in the same time their contribution to the conservation of biodiversity is inestimable.

Trees outside forests have a similar social impact also in countries with abundant forest resources, nevertheless the necessity for protection and conservation of this resource appear less critical and it seems there is a less present concern over their disappearance, but it is appropriate to consider that the degradation of off-forest tree systems is often irreversible and there is a clear risk of ecosystem deterioration.

Trees outside forests play different roles in industrialized countries than in developing ones. For instance, in Italy, in the fifties, TOF produced so much wooden biomass as the proper forests did (Mezzalira, 1997) and the fuelwood coming from small coppice woodlots, tree rows and agroforestry rural hedges was the main source of energy for domestic heating (Pettenella & Serafin, 1999). Nowadays, TOF are often the only source of wood products and energy for rural populations in developing countries, especially where the presence of forest cover is scarce (Biasoli, 2002). On the other hand, in developed areas of the world the role of TOF is more and more strategic in the landscape tissue, less linked to the wood and non-wood productive aspects but more connected to the quality of natural environment and to the living standard of the population (Paletto et al., 2006). In these cases, small woodlots, tree rows and scattered trees, even if with moderate extensions, could function as sink of carbon, especially in agricultural landscape where these formations are the only natural elements able to play the role of storage of biodiversity and of ecological connection (Massa & La Mantia, 1997).

Generally speaking, the integrated sectors of development and sustainable forest and non-forest land management have not paid enough attention to non-forest tree resources, whether rural or urban. Nonetheless, if we look at the environmental and development records, the TOF topic gradually and increasingly appears on the agenda of scientific, economic and policy debates.

The evident climate degradation that took place in the 1970s alerted many countries and provoked a rush of aid to those hit by drought and desertification. This was followed in the 1980s by a wealth of agroforestry research that acknowledged the major role of trees in rural development and soil fertility. Environment, sustainable development and biological diversity were high on the agenda of the 1992 United Nations Conference on Environment and Development (UNCED). During the 1980s and 1990s, the interest increased especially in non-wood forest products. Trees growing outside forests began to be viewed in terms of their contribution to social well-being and to the environment. Policy-makers and planners gradually evolved and converged in their thinking considering a multisectoral and sustainable development of this resource. The importance of tree outside forests and the need for complete and detailed information about these stands were formally underlined for the first time during the FAO Expert Consultation on Global Forest Resources Assessment 2000 (Kotka V, June 1996). During this Expert Consultation, countries expressed their need for assistance and support in providing methods and techniques for a better assessment of the trees outside forest resources. Until that date, several local studies concerning TOF and the value of their resources have been conducted in a scattered and unsystematic way all over the world.

The necessity to develop a coordinated and univocal method to assess TOF that should be applicable in most countries all over the world became an international issue leading countries to mandated FAO for preparing a Thematic Report on TOF as part of Forest Resources Assessment 2010 (FRA 2010), including the formulation of technical guidelines for integrating TOF in the next FRA 2015 reporting process.

On the basis of all these considerations, it is possible to perceive how the qualitative and quantitative characterization and the assessment of TOF are necessary to understand their role and dynamics and to perform the right choices of planning and management with the aim of conservation and improvement of landscape quality.

2. Objectives and structure of the thesis

The aim of this PhD thesis is to investigate TOF formations through the development of a methodology of inventory exploiting the already existing network of large-scale inventories.

Most inventories performed over very large scale (e.g. national inventories) involve several phases of sampling (Corona, 2000). The first phase is usually carried out by means of a systematic search of the study region, in which the region is partitioned into squares or other regular polygons of the same size and points are randomly or systematically selected, one per polygon. In most cases, the layout of the first-phase points can be overlapped on aerial orthophotos or very high resolution satellite images available for the whole study area (e.g. Fattorini et al. 2006; Opsomer et al. 2007) and each point can be recognized and classified. Thus, the first phase of conventional large-areas inventories can be effectively adopted to sample TOF units. Small woodlots and tree rows, are simply selected if they contain at least one of the first-phase points and then their sizes and other physical attributes are directly measured on aerial orthophotos. Scattered trees are included in the sample if they fall within a pre-determinate fixed circular area, centred on the survey points.

Further aim of this thesis was to develop a sector sampling methodology to survey small woodlots in a more expeditious way. The sector sampling methodology foresees sampling plots shaped as circular sectors which could be suitable to overcome the edge effect, while reducing time and effort of the survey and maintaining a good accuracy of the estimate. The sector sampling methodology could be also useful to characterize in rapid and accurate way woodlots on a small scale.

The structure of this thesis is organized as reported below.

Chapter 3 – A classification system for TOF is provided. A review of the main classification schemes elaborated in agroforestry is reported and finally an operational typology of TOF is proposed in which TOF are defined by default respect to the concept of “Forest” *sensu* FAO.

Chapter 4 – A review of the peculiarities for which it is suitable to assess TOF is presented. TOF resources are framed in the main different contexts in which there are commonly found: rural landscape, urban setting, villages and cities and are evaluated from an economical, ecological and social point of view.

Chapter 5 – The thesis framework is analyzed. A literature review of the state of the art concerning studies and researches devoted to sampling strategies suitable for TOF survey and the main research-questions that this thesis aims to answer are presented.

Chapter 6 – A methodology for a large-scale TOF inventory, exploiting the first phase of large-scale multiphase forest inventories, is proposed. Statistical estimators to assess the attributes of small woodlots, tree rows and scattered trees outside forests are developed. The performances of the proposed estimators are checked by means of two simulation studies, one for small woodlots and tree rows and another one for scattered trees. Finally, a case study is performed to test the feasibility of the protocol elaborated in the framework of the proposed methodology.

Chapter 0 – A two-stage sector sampling methodology to estimate woodlot attributes is proposed. The advantages coming from the application of the sector sampling in woodlots are illustrated and a sampling scheme and the statistical estimators are developed. The performance of the proposed estimators is checked by means of a simulation study and a case study is performed to test the feasibility of the developed protocol for the sector sampling methodology.

Chapter 8 – The final consideration on the study and the perspective of the research are reported.

3. Classification systems and definition of TOF

3.1 The FAO classification system

A plethora of environmental systems, ranging from agroforestry and silvopastoralism to rural, urban and peri-urban settings are marked by the presence of trees outside forests and the definition of their exact role in each system is a current issue to better understand the value of this off-forest resource for a sustainable management of lands and of natural resources.

In the last decades, many international organizations and institutional bodies have showed great interest in define and classify the extent of forest resources. This led in the years to a great quantity of documents and publications as result of various studies, researches and specific national and international programs, dealing specifically with the issue of quantification and qualification of the forest resources, with a rising interest in the specific concept of off-forest.

The first issue was of course to pick out an exact definition of TOF. It is of great importance the developing of a land classification that include tree outside forests in the definition, so that these tree resources can be reviewed at each country level and, in particular, can be assessed more easily in the framework of each national forest inventory.

In the intend to carry out an inventory of the trees outside forests resources, in order to quantify the resource in terms of surface or wooden biomass, the unavoidable starting condition is a clear and universal agreement on the typology, the minimum set of variables of the object which has to be inventoried and on the technical guidelines functional to the inventory.

The definition of forest is the starting point for the assessment of forest resources and is one of the key concepts of forest inventories. The definition of forest is of particular importance in large scale inventories for which data on the forest area are undoubtedly fundamental both for comparison among different geographical areas and for the monitoring changes in the same forest area (Kleinn, 2002).

Kleinn (2000) reviewed most of the comprehensive classification schemes which had been elaborated in agroforestry (for example Nair, 1987; Sinclair, 1999), but until that period there was not yet any classification system universally applicable and able to embrace all trees growing outside forests.

Subsequently FAO tried to develop, in different occasions, an official definition of “trees outside forests” and finally it has been accepted by all countries in the framework of the FAO Forest Resources Assessment (FRA) and is annotated in the publication “Trees outside forests – Towards better assessment” (FAO, 2002).

The FAO definition of TOF refers to those trees found on lands that are not “forest land” nor “other wooded land”, *sensu* FAO, and include trees either in rural landscapes (e.g. on farms, in hedges, along roads and streams) or in urban settings (e.g. in private or public gardens, along streets and in the city centres).

The term “trees outside forests” can be considered a neologism, coined in 1995. It defines the concept of TOF by default, with reference to forested areas: an exact definition of the term requires a reading of the definition of the term “forest”.

In this PhD dissertation, the official definitions proposed by FAO reported in the Main Report of Global Forest Resources Assessment 2000 (FAO, 2001) have been adopted for the terms “tree”, “forest”, “other wooded land” and for any other classification of the “total area” of a country. (See Appendix 1).

In 2001, on the occasion of the workshop “Enhancing the contribution of trees outside forest to sustainable livelihoods” (Rome, 26-28 November 2001), FAO defined the category of TOF in relation to trees and tree systems occupying lands other than those defined as “forests” and “other wooded lands”. Consequently, FAO definition of TOF depends on the definition of forest and other wooded land. Accordingly, all those trees and groups of trees which do not fall within the minimum thresholds of extent, width, crown cover and height at maturity fixed for the categories of “forest” and “other wooded lands” and which are on lands deputed to a land use different from forest use, are defined as TOF.

Trees outside forests

Trees (including trees and shrubs, forest and non-forest species) on land not defined as forest and other wooded land. Includes:

- trees on land that fulfils the requirements of forest and other wooded land, except that:

  i) the area is less than 0.5 ha; or
  ii) the trees are able to reach a height of at least 5 m at maturity in situ where the stocking level is below 5 percent; or
  iii) the trees are not able to reach a height of 5 m at maturity in situ where the stocking level is below 10 percent; or
  iv) the trees are in shelterbelts and river galleries of less than 20 m width and 0.5 ha area.

- Scattered trees in permanent meadows and pastures.
- Permanent tree crops, orchards and fruit-tree meadows, industrial fruits trees, coconuts and date palms.
- Trees of agroforestry systems such as coffee, cocoa, home garden, agroforest.
- Trees in urban environments and around infrastructures, such as parks and gardens, around buildings and in lines along streets, roads, railways, rivers, streams and canals.

  (Source: “Trees outside forests – Towards better awareness” FAO, 2002).

The FAO definition of forest is quite specific and facilitates the approach to the definition of the notion of trees outside forests as a non-forest category. Accordingly with the FAO classification of lands, the total land above the sea level can be classified as: wooded land, other land and inland water. The category of wooded land encompasses forest land and other wooded land (Figure 1 and Figure 2). TOF are defined by FAO as "trees on land not defined as forest and other wooded land" and therefore fall within the category of other land. TOF are all those trees and shrubs growing on agricultural lands and built-on areas, which include: agroforestry systems, orchards, small clumps of trees, trees growing on farms, in permanent meadows and pastures, in urban and peri-urban zones, in lines along rivers, canals and roads, in gardens, parks and towns (Figure 3).

However, as it is widely known, the definition of forest lands can vary from country to country in accordance with the environmental stakes, economic interests and local situations involved. Even if the suggestion of FAO to adopt official definitions common for all countries, some national legislation define with its own terminology and thresholds the concept of forest.

Some countries, for instance, have differed as to whether or not classify plantations as forests, while FAO classification of forests, officially defined as forest lands, includes forest plantations.

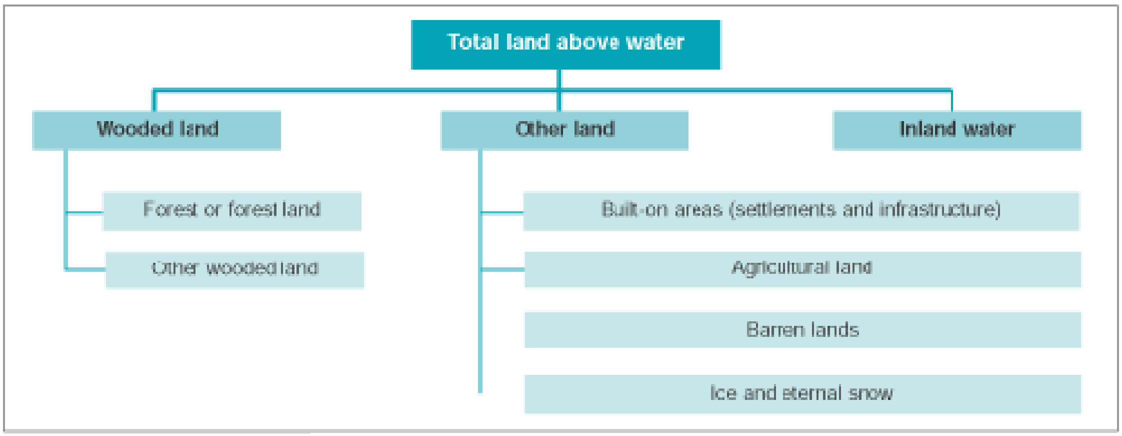


FIGURE 1: CLASSIFICATION OF LAND ABOVE WATER

(SOURCE: TREES OUTSIDE FORESTS - TOWARDS BETTER AWARENESS FAO, 2002)

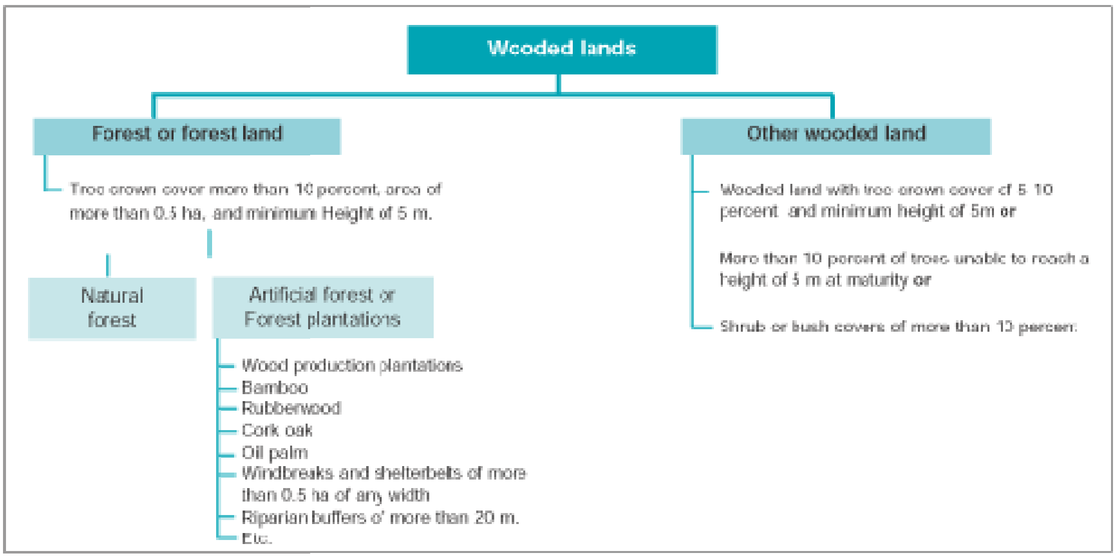


FIGURE 2: CLASSIFICATION OF WOODED LANDS

(SOURCE: TREES OUTSIDE FORESTS - TOWARDS BETTER AWARENESS FAO, 2002)

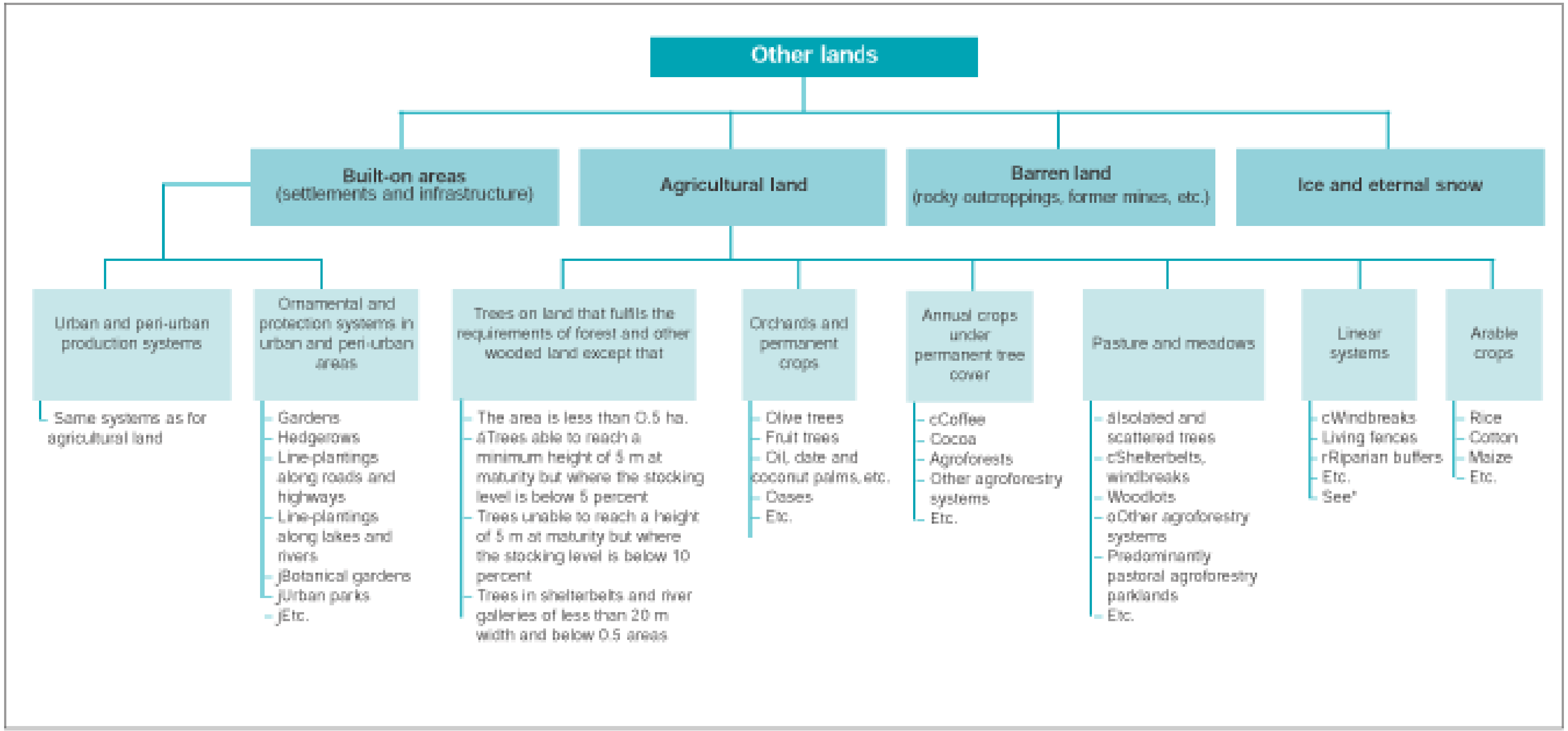


FIGURE 3: PRELIMINARY CLASSIFICATION OF TREES OUTSIDE FORESTS

(SOURCE: TREES OUTSIDE FORESTS - TOWARDS BETTER AWARENESS FAO, 2002)

The latter are defined as forest stands established by planting and/or seeding in the process of afforestation or reforestation, and made up of introduced species or stands of indigenous species, one or two species at plantation, even age class, regular spacing. (FAO, 2001). An example is in Zimbabwe, where the big plantations established for commercial purposes are considered to be forests, but plantations on land used primarily for agriculture are excluded from this category (Moyo, 1999). Sometimes counting plantations as forest area can lead to concealing the extent of forest clearing. Some countries, such as Brazil, Colombia, Haiti, Honduras and Peru, have no legal definition for forest or tree. Moreover, it should be noted that sometimes the definition of forest may be not found strictly in the forest code but maybe in other national laws or codes.

Further examples about diversification in definitions of forest are present across countries in the world. In Bolivia, for instance, the definition of forest strictly depends by the principal land use. In this country, the definition of forest land refers to those areas covered by natural forest, cultivated, intended for various uses, and also lands without trees which may be reforested. Accordingly to this national definition, meadows and pasture, with scattered trees or shrubs, do not constitute forest lands.

In other countries, the definition of forest varies in relation to the minimum threshold of percentage of forest cover. In Chile, for example, forest land is any area covered by plant formations with a predominance of trees, covering an area greater than 5.000 m^2 and 40 m wide, with crown cover of more than 10 per cent (arid and semi-arid zones) or 25 percent in more favoured zones. In other countries, the threshold of forest cover for the definition of forest varies, ranging from less than 10 percent, as in Iran, to 70 percent, as in Costa Rica, and even more, e.g. 75 percent in South Africa. In many countries, the definition of forest is pinpointed by specific forest laws. An example is the case of Gabon, where the Law n° 1/82 (forest and water guidelines) distinguishes two types of forest: protected forests and classified state forests. Protected forests belong to the private domain of the State and may be disposed of and are the preferred area for "customary rights of usage". The state forests include permanent production forests, reforestation plots, national parks for forest use, protection forests, recreational forests, botanical gardens, arboretums and sanctuaries for specific plant species, nature reserves for all plant species, rational game use areas. The law also specifies that customary use rights cannot be exercised within the classified state forests. (FAO, 2010).

3.2 Proposal for an Operational Typology of TOF

A clear definition of the resources to be inventoried is a fundamental starting point for a suitable approach in conducting a valuable inventory of TOF. A good definition should provide unambiguous information of the elements which should be investigate and is required to better understand the structure and composition of the resource (Kleinn, 2000).

In order to facilitate equality in resource evaluation and to guarantee consistency and comparability among data sets, a standardized definition of TOF should be adopted both on a national and international context. This, of course, can also facilitate the scientific communication of data and results among studies. A formal and clear definition system is also particularly necessary to enable universally standard presentations on maps, especially on large areas. It is clear that different definitions could affect inventory's results. The extent with which the results vary with dissimilar definitions depends on factors such as the spatial arrangement of trees and forest patches (Kleinn, 2000), the precision of the data, the land use practices and the legal ownership.

Generally, the criteria used to define forest formations are based on the physical characterization of the natural elements on the land, the Land Cover (LC), or on the principal scope of the usage of that land, the Land Use (LU).

Land cover refers to the aspect and to the physical forms of the land and of the natural elements laying upon it, to their distribution and structure; it is easily observable from aerial photos or satellite views by expert photo-interpreters. It includes the vegetation type, which may be natural or planted, the potential size of the trees, the extent and geometrical shape of formations, the cover percentage and other physical parameters.

Land use is more sensitive and complex to define respect to land cover and refers to the function of land, how it is used and to the activities undertaken upon it to produce goods and services. For instance, in Mediterranean arid zones, especially in areas at risk of desertification, the agroforest is a diffuse type of system; in many cases these are sylvopastoral systems characterized by a relevant presence of trees and the percentage of crown cover could allow to classify these lands as forest or other wooded land, but their primarily use is for grazing. These are the case of the cork oak stands and holm oak forests which constitute the so-called *dehesas* and *montados* of Iberic penisola, the systems dominated by *Argania spinosa* L. in Marocco and *Acacia tortilis* Hayne in

Tunisia, the carob stands and fraxinus forests in Sicily - Italy. Even if the physical characterization of these systems leads to a certain classification, their main function and the activities undertaken upon it are different and leads to another type of classification (Marinelli, 2010).

Therefore, as it clearly appears, these two closely related notions of LC and LU can cause confusion in land classification: a piece of land with uniform cover may have more than one use (FAO, 2002). For instance, in a study on data-gathering on TOF in Latin America (Kleinn et al. 1999), where classification was primarily based on land use criteria, separating land use and land cover aspects was found to be a main source of misinterpretation.

Also the purpose of a definition can influence its content. Biological definitions, for example, are usually based on structural parameters, whereas legal definitions attest to the legal status of land and may ignore the vegetation and land cover. Moreover, many lands legally defined as forests can be temporarily bare of trees even though their status remains unchanged. This is the cases, for instance, of Italy where the national law on forest fires (N. 353/2000) forbids any land use change in burnt forest areas: it is strictly forbidden for 15 years after fire to change land-use, for 10 years to establish building or infrastructures, to hunt and graze, for 5 years to reforest using public funds. Land use changes are monitored through a national Cadastral of burned areas.

Since the management of land and tree resources is usually based on data referring both to LC and LU and given the great variety of forest formations, the diversity of their characterization and the many purposes for which they are intended, a universal definition of forest was arduous and difficult, but all FAO countries for the first time established consensus in the Global Forest Resources Assessment 2000 on a single definition of forest, as reported in previous paragraph.

Also the definition of trees outside forest adopted in this thesis refers directly to the official FAO definitions.

Trees outside forests refer to trees (including both trees and shrubs) on land not defined as forest and other wooded land. This may include agricultural land, including meadows and pasture, built-on land (including settlements and infrastructure), and barren land (including sand dunes and rocky outcroppings). It may also include trees on land that fulfils the requirements of forest and other wooded land except that: the area is less than

0.5 ha, or the trees are able to reach a height of at least 5 m at maturity in situ but where the stocking level is below 5 percent, or the trees are not able to reach a height of 5 m at maturity in situ where the stocking level is below 10 percent, or trees in shelterbelts and riparian buffers of less than 20 m width and 0.5 ha area (Source: FAO, 2001).

This definition pinpoints the global statistical standards for TOF and permits a kind of classification of the different typologies of elements which constitute the category. Nevertheless, the process of developing a single classification system of TOF lands, of focussing on the minimum set of variable to be surveyed in field data collection and of defining the technical guidelines useful for all countries and for each particular conditions, is not easy at all.

A simple classification could be arranged according to the associated land use or to the basic distinction between TOF in natural environments and in utilized landscapes. Moreover, TOF can also be classified according to their origin (remnant trees of former forest, artificially planted trees or naturally regenerated trees, etc.) or according to their management (grown and cultivated for products and services, possibly including silvicultural treatments, or simply accepted and left). Some categories of trees outside forests are associated with the site (which usually implies land use), as for trees on farms, around ponds, in meadows, along roads, in towns, and so forth. Others use the criteria of tree distribution or spatial organization (Alexandre *et al*., 1999), such as line-plantings, single trees, clumps, etc.

Each one of these classification criteria may be useful in different exercises with a particular ecological, political, socio-economic background where the purpose of the inventory could be different from time to time.

It appears clear that in the attempt to develop a classification of TOF lands it is possible to identify different broad categories of TOF stands as a consequence of the FAO commonly accepted definition. Then, within each broad category, different subgroups could be distinguished to finally organize the resulting typology into an operational pattern.

As already explained in previous paragraphs, TOF are defined by default respect to the definition of forest lands and are those trees not recorded as trees in “Forest” nor in “Other Wooded land”. Both “Forest” and “Other Wooded Land” definitions, *sensu*

FAO, are based on a combination of land-use and land-cover features. Consequently, also The FAO definition of TOF derives from a mixture of LU and LC criteria.

The LU criterion is considered when the TOF category is defined as not agricultural land nor urban land. The LC criterion is clearly expressed when we consider a surface of more than 0,5 ha for “Forest” and “Other Wooded Land” and a canopy cover of more than 10% and trees able to reach 5m height specifically for the category of “Forest” and a canopy cover between 5 and 10% and trees able to reach 5m height specifically for “Other Wooded Land”.

Generally, the classification must be practical and should incorporate into a single classification system both the two criteria of land use and land cover. This is particularly true for large area inventories, where all features of TOF lands distinguished in land use and land cover should be assessed on the wide territory of a whole country.

Of course, in classifying TOF and the land where TOF are found, a key question should be to take in consideration the biophysical parameters of land cover and the land use, with particular regards toward socio-economic aspects (Kleinn, 2000). Once established that the TOF definition imply a conjunction of land-use and land-cover criteria, to better identify different categories of TOF stands it is necessary to examine in which local situations TOF formations can be found and how they are spatially arranged.

In regard of all these considerations, during the Inception Workshop (FAO, Rome, 7 – 10 June 2010) for preparing a Thematic Study on TOF with the aim to integrate TOF in the FRA 2015 reporting process, four broad categories in which TOF may be encompassed have been examined by the main experts at global level.

The proposed four categories are reported below:

1) TOF can be structured in tree stands similar to “Forest”, with trees able to reach 5 m of height and more than 10% of canopy cover, but which extend on a surface smaller than 0.5 ha. These TOF formations are located on land typically defined as “forest” as per FAO definition, in regard of the land-use criteria (neither on agricultural land nor on urban land), but they don’t fulfil the definition of “forest” because of their physical extent.

2) Another typology of TOF stands is similar to “Other Wooded land”, with trees able to reach 5 m of height and a canopy cover between 5 and 10% or with a

combined cover of shrubs, bushes and trees more than 10%, but which present an area smaller than 0.5 ha. As for the previous category, these TOF formations are located on land typically defined as “Other Wooded land” as per FAO definition, in regard of the land-use criteria (not agricultural land, not urban land), but they don’t respect the minimum size defined for “Other Wooded land”.

3) TOF can be considered also as all those tree stands established on lands used predominantly for agriculture purpose. In this case any land-cover criterion is adopted, but the definition is based only on the land-use condition.

4) A further typology of TOF comprises all those tree stands placed in urban settings. Also in this case any land-cover criterion is adopted and the definition is based only on the land-use condition.

According to what has been explained so far, a logical identification of TOF category leads to the recognition of three main typologies of categories for TOF that are relatively easy to distinguish.

A) Small and isolated tree or shrub stands: these stands are similar to “Forest” or to “Other Wooded Land” but with an area smaller than 0.5 ha, on land that is not under agricultural nor under urban use. The trees which constitute these stands may have been planted, sowed or naturally regenerated (small woods, small woodlots);
B) Trees in agricultural setting, whatever the size and shape of the stands;
C) Trees in urban setting, whatever the size and shape of the stands.

Each typology can be subdivided into sub-categories.

A) Small and isolated tree/shrub stands on forest land.

TOF in this category are assembled in small “Forest” or in small “Other Wooded Land”, but they are not different in nature from trees assembled in either “Forest” or “Other Wooded Land”, except for the minimum surface. For this category there is no need for a further sub classification.

B) Trees in an agricultural setting.

TOF in this category have a different nature than the trees assembled in “Forest” or in “Other Wooded Land”. They are the result of a human choice to keep or to plant trees and to integrate them into the farming system in a rural landscape.

A first distinction inside this category could be made between TOF depending from farms and TOF independent from farms.

B.1) TOF on farms.

This category encompasses the effects of the whole range of agroforestry practices carried out on a specific rural context. Trees in this sub-category can present a great variety of possible organizations and spatial configurations.

As outlined in the “General classification of agroforestry practice” proposed by Fergus Sinclair (1999), agroforestry, as it is practiced, is very rarely a whole farm or forest system. It is much more common for trees to be used in various productive niches within a farm, as how “agroforestry” is defined also by Gordon et al., 199 and Leakey, 1996.

Each instance of tree use on a farm, or of agricultural integration in forests, is for a purpose or set of purposes, and has characteristic components and management. This makes it more useful, from an agroforestry perspective, to classify and describe such practices and the trees involved in such practices, considering their role within the systems of which they form a part, rather than to attempt to classify the whole farm or forest systems that they are in.

Scaling up to landscape and regional levels, agroforestry is in concrete a mosaic of agroforestry patches having different species, ecological structures and utility.

This view of agroforestry can be resolved in definitional terms by distinguishing between agroforestry on the one hand as an approach to land use and on the other as a set of integrated land use practices (Sinclair, 1991).

The approach is interdisciplinary and combines the consideration of woody perennials, herbaceous plants, livestock and people, and their interactions with one another in farming and forest systems. Consideration of social as well as ecological and economic aspects is implied. The set of land use practices involve the deliberate combination of trees (including shrubs, palms and bamboos) and agricultural crops and/or animals on the same land management unit in some form of spatial arrangement or temporal sequence such that there are significant ecological and economic interactions between tree and agricultural components (Sinclair, 1999).

In the light of such considerations, the sub-category has been further subdivided considering spatial configurations and land use practices.

B.1.1) Trees in dense stands, not allowing cultivation of grain crops in between trees, except only during early stages: orchards (partly), tree-crop plantations, tree-based homegardens, and woodlots;

B.1.2) Trees dispersed, or scattered, allowing cultivation of grain crops or grazing in-between trees: orchards (partly), agroforestry parklands, trees on pasture, trees in fields, etc;

B.1.3) Trees zoned in linear features, localized in specific places on farm, that may be on boundaries (live fences, hedges), on contour or in rows (“alley-cropping”, hedgerows).

B.2) TOF in rural landscape but independent from farms.

Trees under this category are usually under collective management and they are treated in a common and more uniform way by the designated authority of village, district, province, state, etc. As result, these patches of the agroforest landscape are subjected to fewer and more homogeneous land use practices and they appears uniform to their inside.

Trees in this category are mainly represented by *linear features*:

B.2.1) Trees along waterways (streams, rivers, canals, etc);

B.2.2) Trees along roads.

C) TOF in urban setting

TOF are also in this case the result of a human choice to keep or to plant trees and to integrate them into the urban life cycle. As for TOF in an agricultural setting, we may also distinguish between TOF depending from individual houses, under private management, and TOF independent from individual houses, under collective management.

C.1) TOF depending from individual houses.

Trees are part of private gardens and they may perform various functions as fences on property boundaries, for shade or visual pleasure. As a consequence, they present different spatial distributions and can be sub-classified as:

C.1.1) Trees on boundaries (live fences);

C.1.2) Trees inside private gardens.

C.2) TOF independent from individual houses.

Trees are here usually on public land and are under collective management in villages, cities administrations, etc. They can be sub-classified as:

C.1.1 Trees along streets;

C.1.2 Trees along waterways (canals, streams, rivers);

C.1.3 Trees in public parks.

According to the presented classification, one logical way to identify TOF categories for the assessment of this resources taking into account both LU and LC, would be to recognize first the broad category of setting, relatively to the land-use of the area if it is forest land, agricultural or urban setting, and to descend the hierarchy as much as possible by distinguish between different spatial structures, as reported in TABLE 1.

An alternative approach to identify TOF categories for the assessment would be to consider first the land cover, recognizing the spatial structure of the TOF stand, and then to look at the setting and the relative land use (Table 2).

TABLE 1: CLASSIFICATION OF TOF BASED MAINLY ON LAND USE AND THEN ON LAND COVER.

TOF	**Forestry setting**	Trees in Forest/Other wooded land < 0.5 ha	
	Rural setting	Trees along roads	*Independent from farms*
		Trees along waterways	
		Trees in dense stands	*On farms*
		Trees scattered	
		Trees in linear features	
	Urban setting	Trees along streets	*Independent from houses*
		Trees along waterways	
		Trees in public parks	
		Trees on boundaries	*Dependent from houses*
		Trees inside private gardens	

TABLE 2: CLASSIFICATION OF TOF BASED MAINLY ON LAND COVER AND THEN ON LAND USE.

TOF	**Dense stands**	Forest land < 0.5 ha
		Farm land (tree crops, orchards, agroforests, etc)
		Urban setting (public parks, large private gardens)
	Scattered trees	Forest land < 0.5 ha
		Farm land (orchards, agroforestry parkland, trees in fields or pasture)
		Urban setting (small private gardens)
	Linear features	Trees along street or road (urban or rural setting)
		Trees along waterway (urban or rural setting)
		Trees on boundary (farm or urban setting)
		Trees on contour (farm setting)
		Trees in hedgerow (farm setting)

3.3 Classification of TOF

The definition of TOF adopted in the work presented in this thesis is in accordance with the last Italian National Forest Inventory (INFC, 2005 see http://www.infc.it), which refers directly to FAO definitions.

One of the main aims of the last Italian NFI was in fact to produce information needed for international reporting activities such as FAO assessments of forest resources extent, carbon sink estimates for the Kyoto Protocol and sustainability evaluation of forest management within the Ministerial Conference on the Protection of Forests in Europe (MCPFE) process.

Therefore, by defining the inventory domain and the survey procedures of INFC, particular attention was paid to the international standards and commitments. It has been decided to base the inventory domain on the FAO-FRA2000 definitions. and to include both forest and other wooded land use. Moreover, besides the more traditional dendrometric and silvicultural attributes, the data collection involves more detailed measurements about above-ground phytomass and ecological features to provide data on carbon sequestration and to meet most of the commitments related to the MCPFE. In relation to the carbon stock estimates, the INFC provides our country with updated and reliable data on the extent of forests, on the volume and the dry weight of above-ground phytomass and dead wood, on growth rate, and on the carbon content of litter and organic soil (Tabacchi et al., 2005)

It is important therefore that an inventory definition, at regional or national scale, is consistent with the ranking levels of the classification and, possibly, with the international standards, in relation also to the Kyoto Protocol and the successive agreements of Bonn (2001) and Marrakesh (2002) (De Natale et al., 2003). In fact definitions based on different criteria can cause even considerable dissimilar results in the classification of the forest cover (Tosi & Monteccone, 2004).

The second Italian NFI is a three-phase stratified sampling inventory and, in particular in the first phase, classification is consistent with the FAO-FRA2000 definitions and with the first level of *CORINE Land Cover* System, with a single class including both “forest” and “other wooded land”; while the lower levels, related to the distinction of the various phytocoenosis, correspond the European system of classification of natural environments, known as *CORINE Biotopes*.

In the first phase, a systematic unaligned sampling of approximately 301.000 points distributed on a grid covering the whole national territory were observed on black and white digital orthophotos with a nominal scale of 1:10.000. Through photo interpretation, the polygons on which the sample points fall were classified in five main land use/land cover classes (Artificial surfaces, Agricultural areas, Forest and semi-natural areas, Wetlands and Water bodies) and subclasses.

The essential condition for which an element is classified in the respective land use class is to belong to an homogeneous whole of a minimum surface of 5.000 m^2 and/or of a minimum width of 20 m, in case of linear elements. In case that the minimum thresholds of width and extent are not satisfied, the element is considered as an object included in the surrounding polygon, with the same land use.

Groups of forest trees large less than 5.000 m^2 and 20 m of width, in case of linear elements, have been considered as “forest formations included in non-forest land” in the first phase of the NFI, referring in particular to *small woodlots* and *tree rows* included in non-forest land and to *scattered trees*:

Small woodlots – groups of trees with an area comprised between 0.05 ha and 0.5 ha and of width more than 20 m.

Tree rows – trees in shelterbelts, windbreaks and woody buffer strips with a minimum of three trees of width more than 3 m and less than 20 m and longer than 20 m.

Scattered trees – All trees or group of trees not included in forest, small woodlots and tree rows.

“Forest formations included in non-forest land” should be classified relating to the land use of the surrounding area and to the land cover (Table 3).

TABLE 3: LAND USE/LAND COVER CLASSIFICATION OF "FOREST FORMATIONS INCLUDED IN NON-FOREST LAND" ADOPTED BY THE ITALIAN NFI (2005).

LAND USE/LAND COVER CLASSIFICATION	CLASSIFICATION OF FOREST FORMATIONS INCLUDED IN NON-FOREST LAND
Artificial surfaces	Small woodlot included in artificial surfaces.
	Tree row included in artificial surfaces.
Agricultural areas	Small woodlot included in agricultural areas.
	Tree row included in agricultural areas.
Forest and semi-natural areas	Small woodlot included in rangelands, pasture lands and fallows and areas with sparse or absent vegetation.
	Tree row included in rangelands, pasture lands and fallows and areas with sparse or absent vegetation.
Wetlands	Small woodlot included in wetlands.
	Tree row included in wetlands.
Water bodies	Small woodlot included in water bodies.
	Tree row included in water bodies.

4. Why assess TOF?

Trees outside forests correspond to a great variety of settings and uses, and cover a wide range of shrub and tree formations. They can be found in productive systems such as orchards and trees in agricultural fields, TOF can have protective, ecological or landscaping functions; they can have also ornamental significance such as trees in home gardens around houses, in parks and towns. They can be natural elements or planted. In spatial terms, they may be scattered on farmland and pasture, or growing in tree rows along roads, canals and watercourses, around lakes, in towns, or in small aggregates such as clumps of trees, sacred woods, urban parks (Alexandre *et al*, 1999).

In many cases TOF form an integral part of household production and income, providing wood and non-wood products as well as direct and indirect services. They supply food and feed products of crucial importance for many populations, such as fruits, seeds, nuts, fodder and browse, and non-food items such as pharmaceutical products, timber, chipwood, fuelwood, fiber, leaves, and so forth. Non-forest systems offer also many direct services such as better environmental quality, ecosystem conservation and shade, as well as indirect services such as possibilities for jobs, the development of industrial and artisanal sectors and market openings.

This implies the involvement of many and varied disciplines, from agronomy to urban planning, sociology and biology, with particular focus on the spheres of forestry, agriculture, environment and livestock production. They are a crucial and core element of rural, urban and peri-urban systems.

Trees in rural landscapes

The interest and the custom to keep trees in rural setting is widely recognized and applied: shade and shelter, environmental protection, and enhancement of rural and scenic surroundings are the main reasons cited by industrialized country farmers for leaving trees standing in their fields (Auclair *et al.*, 2000). In the same way, in the developing countries farmers are particularly apt to favor, select and plant species which can offer a range of goods and services.

Trees in rural settings have been integrated for centuries in the local land use systems of farms, according to the agro-ecological and socio-economic conditions of farmers.

Trees in rural landscapes contribute to diversified rural income and they are decisive for the subsistence of millions of people (FAO, 2002). The products derived from trees in rural landscape, both dependent or independent from farms, are traded on local, national and international markets and their use varies from food to medicine, cooking fuel, animal fodder, construction materials, and so forth.

In addition, trees in rural landscapes provide protective functions: they contribute to the water erosion control and watershed protection, to a more efficient use of water and nutrient resources, to microclimate moderation, biodiversity conservation. For example, trees are used in integrated riparian management in the US to filter out nitrates and phosphates from water running into streams (Williams et al., 1997) and in Australia to lower saline water tables to prevent salinization of agricultural land (Schofield, 1993).

The International Council for Research in Agroforestry (ICRAF) defines agroforestry as a dynamic, ecologically based, natural resource management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production, enhancing social, economic and environmental benefits for land users at all levels.

Trees play a specific role also in livestock production systems. Their presence and distribution may be intentional and not simply left to chance and TOF can unequivocally mark the character of livestock production in a given landscape, depending on the presence or distribution of specific trees. In arid and semi-arid zones they can mean the difference between life and death: trees are the only source of green forage during the lean periods before the rains. Moreover, trees outside forests provide many other services for livestock: they offer comfort and shelter for animals, and mark the boundaries for herd access and movements.

Also silvopastoral systems are frequently characterized by the presence of tree species that may be grown spontaneously or may be planted in association with local or introduced species. Shelter-providing hedgerows and woodlots, like windbreaks, are commonly combined also with grassland.

Every agrosilvopastoral landscape has its own unique character in terms of the production usages and tree species favored or established.

Trees in urban setting, villages and in cities

Trees in urban settings are not less important: they are found in private home-garden, along streets, in public gardens and parks and provide fundamental functions and services, such as microclimate moderation, “green” environment conducive to good health and aesthetic and ornamental value.

In the Tropics, trees of home-gardens are also an essential component of the life of people in villages and cities, where they provide an important part of the fruits, cooking fuel, and construction material needed and used at family level. Trees outside forests have also been called "trees that nourish" (Bergeret and Ribot, 1990), a term which is really meaningful for landless people who make beneficial use of the tree products to which they have access. Women, the first to be concerned by this harvest, possess the skills to store and process these leaves and fruits so that they will be on hand to feed the family all year round. A study done in Java showed that 60 percent of the family's food comes from home gardens in which trees are prominent, and that these gardens are mostly managed by women (FAO, 1989).

Tree outside forest are also useful to provide material for construction: over a million people live in houses either made of bamboo, or which use bamboo as a structural element, wall-panels, or roofing (Kumar and Sastry, 1999), even if the designation of bamboo as forest or non-forest resource could depend on the country.

However, city trees depends as much on the demand from city-dwellers and have to adapt to many constraints, such as lack of space and soil, air pollution, damage by man, animals and cars, and repeated cutting. For these reasons these trees need targeted protection and planning for management.

Trees outside forests constitute also urban forestry. Urban and peri-urban forestry includes the management of single trees and clumps of trees which have either sprung up by themselves or been planted in urban areas (FAO, 2002). The term “urban forestry” embraces tree cropping, green spaces and afforested peri-urban areas. The quality of life and the aesthetics of the landscape closely depend by the presence of these off-forest formations, especially in highly industrialized and anthropic environment as cities and megacities.

Urban and peri-urban forestry is increasingly involved in the ecological and scenic aspects. Integrated urban land management is becoming a core feature in big cities of industrialized countries and, furthermore, most urban agglomerations in developing countries are also budgeting and planning for urban trees.

4.1 Economic, ecological and social value of TOF

Trees are an integral part of many non-forest environments and are commonly widespread in rural and urban settings. Despite their ecological, economic and social importance trees outside forest were long overlooked by law and policy in the failure to view these trees as a separate entity.

If TOF are well known to farmers and urban dwellers who manage their own land at local scale, they are not so well know by managers at national scale. TOF are in most countries a resource which is poorly defined and weakly reported in official statistics. It is a resource which is often ignored in land-use planning and development policies and for which clear legal regulations and management plans do not usually exist.

But this viewpoint is changing and an interest is mounting in trees outside forest, also from international institutions, leading the theme on the scientific, economic and policy debate of the actual environmental and development processes.

Environment, sustainable development and biological diversity were high on the agenda of the 1992 United Nations Conference on Environment and Development (UNCED), which marked a turning-point in approaches to development. Tree-planting was encouraged, particularly for carbon storage. Yet since during the 1980s, a wealth of agroforestry research highlighted the major role of trees in soil fertility and rural development. Moreover, in the 1980s, interest mounted particularly also in non-wood forest products, previously considered minor products compared to wood. Consequently to this rising interest in TOF, there was also an increasing need for data on all tree resources.

In the last decades, trees outside forests became to be considered in terms of their contribution to social well-being, to the economy and the environment. Nowadays, their productive, ecological and social roles put rural and urban trees on a similar footing of forests.

From an economic point of view TOF play a key role for the livelihood of many people. This resource furnishes a great variety of environmental services as well as products for direct consumption or processing by rural households or for sales, with a real market value, supporting small scale economies.

It is hard to assess the economic contribution of trees outside forests at the local level and even harder and more complex at national and international levels. Wood and non-wood products from off-forest trees appear into the statistics only when traded on official, national or export markets, and, even here, the statistics fail to differentiate between forest and non-forest products. This is the case of gum Arabic, sheanut, cocoa, coffee, tannin, and so forth, a portion of which is produced on small farms and sold in non official market. An idea of the economic value of these goods and functions can come by reviewing the various benefits of wood and non-wood products and services in the forest sector.

Off-forest trees are thus perceived as a means of enhancing alternative production systems and satisfying the need for energy, services, wood and other “forest” products, especially in areas with scant forest resources. This may produce forest policies that give consideration to how farmers and rural people use these trees. In Libya, non-wood forest products play an acknowledged role in rural economies (FAO, 1993). Forest policy in Niger has supported wood supply schemes and the establishment of rural woodfuel markets (Bertrand, 1993).

However, the extent to which national forestry policy guidelines cover trees outside forests is quite often influenced by the extent of forest cover and the economic role of wood. In countries with extensive forest cover, the state will intervene in the logging sector, stimulating the wood industries and fostering tree-planting, and trees outside forests will receive less consideration. In arid countries with scant tree cover TOF are much more integrated in the forest and agricultural policies (FAO, 2002).

Trees outside forests also play a key environmental role. They mark off territorial boundaries, a first stage in land appropriation, demarcate holdings, decorate living quarters and provide shade for man and beast in warmer countries. Shade trees are beneficial components also in many agroforestry systems such as coffee, cocoa and tea plantations. Trees outside forest play a key role also in conservation of biodiversity and often scattered trees represent elements of connection for many animals and birds, particularly in zone with slight tree cover.

Furthermore, trees outside forest can give a fundamental contribution in quantitative terms in the production of biomass for energy. European environmental policies, as well as those of other countries, increasingly are promoting the use of clean energy coming from renewable sources (i.e. Directive 2009/28/EC). This is leading to the construction of several plants for production of energy from vegetal biomass or derived products, such as vegetal oils or biogases from fermentations. Nevertheless, many of these power plants work with bio-fuel coming from far away areas; this process can cause high transportation costs and excessive CO_2 emission related to the transport, reducing the benefits coming from the use of renewable energy as an alternative to fossil fuels. This is the case of *Jatropha curcas* L., whom seeds contain 30-38 % of heating oil, which is native from Central America and is cultivated in tropical e sub tropical areas of Asia and Africa and which is used to power many energy plants of European continent. TOF if well assessed and managed can provide a high contribution in production of biomass useful for energy purposes, containing the need of biomass coming from other countries (Barbati et al., 2009).

Moreover, a relevant consideration of TOF resources concerns the potentiality in contributing to store carbon dioxide, functioning as sink of CO_2. The possibility to assess this capability is of fundamental importance in the current international political scenario of climate and global change. To succeed in defining and evaluating how much CO_2 is actually stored in these non-forest formations could give a different and real position of each country in the context of European and international carbon credits market, within the framework of reduction in carbon emissions accepted and ratified by 184 Parties with the Kyoto Protocol of the UNFCCC, edited at Kyoto on December the 11st 1997 and became effective in 2005.

Trees outside forest play also an important social role. They are fundamental for creating high-quality environments for millions of people by providing new opportunities for leisure, recreation, jobs and cultural activities, supporting education, healthy living and social and economic development. This is the case of “Social Forestry” which has advanced significantly since the 1980s, mainly in response to the problem of supplying fuelwood for rural communities. Social forestry aims at raising trees and plantations by the common man so as to meet the growing demand for timber, fuel wood, fodder and so forth, thereby reducing the pressure on the traditional forest area. It is often associated with rural development (Sharma, 1993), as in India, where forestry policy began to consider social forestry as a means of reforesting unused community and national land.

The same can be said of “Community Forestry”, a particular form of “Social Forestry”, which also underscore the responsibility of user populations for tree resources. “Community forestry” is a village-level forestry activity, decided on collectively and implemented on communal land, where local populations participate in the planning, establishing, managing and harvesting of forest crops, and so receive a major proportion of the socio-economic and ecological benefits from the forest (Martel & Whyte, 1992). Community forestry was established in 1990 in England and has demonstrated the potential contribution of environmental improvement to economic and social regeneration, preparing and addressing positively for climate change, enhancing biodiversity and improving quality of life by working with existing communities to plant trees, create local green spaces and promote local food growing; to minimize flood risk, storm water flows and be linked to local food and fuel, providing diverse benefits to the local economy to the existing and future generations. In managing these tree resources, these people also become the agents of their own development (Thomson, 1994).

Trees outside forests are sometimes invested with symbolic, cultural, and even religious value. They cover so many aspects of culture: language, history, art, religion, medicine, politics, and more. Folklore, stories and proverbs also attest to the symbolic significance of trees (Calame-Griaule, 1980 and Kaboré, 1987, cited in Boffa, 2000b). They are sometimes called "trees of wonder", when due to their venerable age, isolated trees have reached impressive size and passed into local legend. Watkins (1998, cited in FAO, 2002) has shown how such trees are valued in the U.K. for their beauty, solemnity and mystery.

4.1.1 Wood products

4.1.1.1 Fuelwood

Wood and biomass are still the most widely used source of fuel in the developing countries, where the 81 percent of the whole wood harvested is utilized as wood fuel. This percentage varies between 91 percent for Africa, 82 percent for Asia, and 70 percent for Latin America. On the contrary, in industrialized countries, traditional wood fuels account for only seven percent of energy consumption in (FAO, 2002).

Few studies give an aggregate fuelwood production assessment for trees outside forests, however an idea can come from the management of agroforestry systems.

While the production of fuelwood is not the main purpose of orchards, that is often an important secondary effect, especially in the developing countries. Olive tree pruning and rejuvenation in Morocco usually accounts for 0.8 to 1.5 m3/ha/yr of wood fuel, depending on the climatic zone (M'Hirit and Et-Tobi, 2000, cited in FAO, 2002). Trees such as laurel (*Cordia alliodora* Oken), grown for shade in the coffee and cocoa plantations of Central America, supply both fuelwood and timber during the 10-15 years of their rotation (Somarriba, 1990). A study state that 1 km of coppiced hedgerow in France produces 8-15 steres of wood/yr, the energy equivalent of 1500-2000 litres of fuel (Schmutz *et al.,* 1996, cited in FAO, 2002).

More surprisingly, also trees outside forests in the urban forestry context are considered a source of fuelwood. In small, tropical, urban areas of Asia and Africa, a quite substantial proportion of the wood burned is gathered inside the towns (Kuchelmeister, 2000). On the contrary, in the industrialized countries, especially in North America where urban forestry is well-developed, tree residues are under-utilized. A study in the United States showed that only 6 percent of the 13.5 million m^3 of urban woody residue is used as fuel and the remnant part has not any direct utilization (Whittier *et al*, 1995) and maybe is smaltita as waste. Fuelwood is strategic for the production of bioenergy, as well as biogases or vegetal oils coming from plant wastes, and can generate remunerative incomes especially where non-forest trees grow near these wood-fuelled power stations.

4.1.1.2 Timber and wood services

Timber is not generally the principal end product of off-forest tree resources. However off-forest tree resources can provide wood for planks, poles, beams, and are commonly used by farmers as roofing materials for houses, to construct fences, furniture and transport items such as wheelbarrows and carts.

There is also some exceptions: in Sri Lanka, for instance, the timber coming from TOF cover more than 70 percent of the supply of construction and industrial wood. Wood from the pehibaye palm (*Bactris Gasipaes*) is marketed to make parquet flooring in the American tropics (Clément, l989).

In Central America, Beer *et al* (2000) report a potential productivity of 21.8 million m^3/yr of sawn logs, assuming an effective harvesting of the tree products of shade plantations and some silvopastoral systems.

In India there are associations of forest industries and small agricultural enterprises for the production of timber and service wood and small farmers in KwaZulu-Natal in South Africa receive support from paper pulp producers (Arnold, 1998, cited in FAO, 2002).

4.1.2 Non-wood products

The "non-wood forest products" (NWFP) are non wooden goods coming from forest species and, as per FAO definition, encompasses also products coming from trees outside forest: "non-wood forest products consist of goods of biological origin other then wood, derived from forests, other wooded lands and trees outside forest" (Unasylva, 1999).

Non-wood forest products are among the oldest trade goods in the world. In the year 2000 B.C. the Egyptians were already importing gum Arabic from the Sudan for food, paints, gum and for use in mummification (Seif el Din and Zarroug, 1996, cited in FAO, 2002). Pine resin has been harvested in temperate zones for over 2000 years (Vantomme, 1998, cited in Taylor, 1999). The international trade in sandalwood oil, for example, goes back to before the twelfth century (Roe et al., 2002, cited in FAO, 2002).

The trade in non-wood products, such as ornamental plants, mushrooms, and other edible and medicinal plants, can bring to great incomes, as for instance, about US$ 130 million in China from the export of edible bamboo shoots (Kumar and Sastry, 1999) and an annual US $200 million in the Pacific Northwest (Hansis, 1998, cited in Taylor, 1999).

When forest resources decrease and the need for certain non-wood products mounts, trees growing outside forested areas become increasingly important in meeting the demand.

Particular importance was given by scientists in the 1990s to non-wood health products, such as natural foods with therapeutic properties, capable of halting or averting the development of certain diseases. These extensively, even if informally, traded products are socially and economically valuable and the demand for such products is intended to rise as both the world's population and the research in this pharmaceutical domain increase.

A key factor in the success of non-wood forest products is local processing to preserve them, reduce post-harvest losses, and reach distant markets, all of which add significantly to the value of the resource.

4.1.2.1 Fruit and seeds

Fruits and seeds are mostly derived from cultivated tree orchards or agroforestry systems. In industrialized countries fruit trees are intensively managed and are frequently monocropped and genetically improved. Usually, in agroforestry systems fruit production is not as structured as the traditional fruit tree cultivation circuits. Traditionally, in heavily populated areas of the tropics, in home gardens trees and shrubs are grown in association with annual or permanent farm crops and/or livestock farming, and provide fruits and other products for rural populations.

The desert date palm (*Balanites aegyptiaca* (L.) Delile) produces an estimated 100-150 kg of fruit per mature tree each year. Shea nut (*Vitellaria paradoxa* C.F. Gaertn) is outstanding, producing an average 48-65 kg/ha/yr of dried nuts. Shea nut-linked activities can account for some 20-60 percent of the income of women in Burkina Faso. Aside from timber and fuelwood, its main value lies in the myriad uses made of its fruit (Bagnoud *et al*, 1995). The pulp is eaten raw, and the kernel supplies oil used in cooking, cosmetics, candles, and even for waterproofing the walls of farmers' homes. In addition to these local functions, shea nuts are exported for use in cosmetic, pharmaceutical and bakery products. The economic value of shea nut trees is of fundamental importance for the livelihood of many populations.

Also coffee production, coconut and cocoa are key factors in local development, driving the little economy into the world trade. These crops not only supply income to local farmers, they offer the added benefit of a crop whose productive life can extend over several generations on a quite small area, much of it farmer-owned (Follin, 1999, cited in FAO, 2002).

Coconut, an extremely hardy crop, provides food, drink and various kinds of useful materials to local populations and the coconut sector is often subsidized for the export of coconut vegetal oil (FAO, 2002).

4.1.2.2 Foliage and fodder

The livelihood of pastoralists in tropical areas derives primarily from animal farming, which depends from the availability of herb, fodder and browse. Where grasses are scarce tree foliage becomes an essential source of livestock feed. Tree species play a leading role in feeding livestock in the more arid parts of the world, where grassland resources do not provide enough good quality feed for all the year.

In some cases, fodder resources have been overexploited: where branches are often broken and the bark is gnawed away leaving wounds, the danger of attack by parasites is high. Over-grazing can thus endanger the natural regeneration of some tree species. One example is Yeheb (*Cordeauxia edulis* Hemsl.), an endemic, semi-arid shrub of the central plains of Somalia and Ethiopia, which has become over utilized and is today in danger of extinction. Its natural regeneration is severely threatened since it is used as main seasonal feed source for animals like camels and goats, fire wood and food for humans (Johansson, 2006).

To avoid similar threats, such systems need to be rationally managed. In Asia, for instance, farmers are beginning to plant trees for fodder, among other uses.

4.1.2.3 Gum and bark

Most gums, resins and latexes coming from off-forest systems are items widely used and traded all around the world. Examples are the latex from rubberwood, produced in both forest plantations and agroforestry systems, and the commercially and industrially valuable product represented by gum Arabic, of which the top world producer is Sudan. These non-wood off-forest products can generate high incomes if the production system is well managed and organized: gum Arabic is an inestimably valuable component of more than one industry and any synthetic substitute has replaced it.

Trees off-forest can also provide popular beverages made from sap, like the familiar palm wine, made from species such as *Borassus aethiopum*, *Hyphaene coraiacea* and *Phoenix reclinata*. Palm wine daily production in Mozambique is of around 20 l/day, and represents a lucrative year-round activity for farmers. In the Bassila region of Benin, palm wine-making and the related distilled product is the only tree-linked enterprise which can entirely cover a person's subsistence costs (Boffa, 2000).

The bark of *Prunus africanum* yields an extract used in powdered form in traditional medicine in Cameroon and more than 3.500 t of bark are harvested every year, this is leading the species to risk of extinction (Spore, 2000, cited in FAO, 2002). Also *Irvingia gabonensis* and shea tree barks are exploited locally for their medicinal properties, and *Grewia tenax* bark in Sudan is used to make toothbrushes. Tree bark may have wider commercial uses, for instance cork from cork oak (*Quercus suber*), which grows especially in *dehesas,* typical agrosilvopastoral systems common in southern Europe.

4.1.2.4 Flower and essential oils

Flower essential oils, honey and other apiculture products are also derived from trees outside forests. These products are of interest to the food, pharmaceutical and cosmetic industries and they can constitute a lucrative secondary income for many small farmers.

The extraction of essential oils is at the basis for the production of cosmetic products.

Apiculture is popular in many rural realities with the production of different kinds of honey, wax and other products. Ethiopia follows China, Mexico and Turkey as the world's fourth wax producer with averaging 3.000 t/yr, and is fifth in order of exports (Deffar, 1998).

4.1.3 Environmental resource

In the story of the earth, it took two million years to arrive at the one billion of people alive on the planet by the year 1800. By the year 2025, world population is projected to approach nine billion, of whom over seven billion in the developing countries. One billion people live in poverty and 925 million, which is 13.6 percent of the estimated world population of 6.8 billion, never get enough to eat (FAO, 2010), although the world produces much more food than it is necessary to feed everyone. The principal problem is that many people in the world do not have sufficient land to grow, or income to purchase, enough food.

The challenge is clearly to ensure that the efforts for natural resource conservation and sustainability are sufficient to reduce poverty and ensure sufficient livelihood to guarantee food security for the present and future inhabitants of town and countryside.

Trees outside forests can play a leading role in meeting resource conservation and management needs in both rural and urban areas. Urban forestry, for instance, is already crucial to environmental quality, and will be increasingly in the future, thanks to the unequivocal ecological benefits which provides in enhancing the climate, recycling waste waters and attenuating atmospheric and noise pollution.

4.1.3.1 Soil and water protection

Trees outside forests have the universally acknowledged role in halting the advance of the desert, checking wind and water erosion, facilitating the percolation of rainwater and enhancing agricultural production in the long term, as for instance through nitrogen-fixing tree species. Whether in dense stands or in line plantings, scattered or in hedgerows, trees preserve the organic matter contained in the soil and increase its fertility.

In many examples, especially in the South of Sahara trees are used outside forest to fix dunes and combat drought. Examples are in Mauritania where 800 km of windbreaks have been planted to hold back the advance of the desert (Ben Salem, 1991).

Oases in Iraq intercrop a top story of palms, an understory of fruit trees and a ground crop (*ibid.*), a proven technique for checking wind erosion. Farmers in the mountainous areas of Iran leave 20 to 100 trees/ha standing on farmland to ensure soil and crop protection. For the same reasons, Afghan farmers grow mulberry trees, poplars, and eucalypts and fruit trees around their plots and along irrigation canals (FAO, 1993). In arid African regions, single trees such as *Faidherbia albida* preserve soil fertility, protect the grass, and provide shade and shelter for people and animals.

In Egypt, Iraq and Libya, windbreaks have a substantially positive impact on production yields (FAO, 1986).

In much of the world, pioneer encroachment upon the forest is a factor in natural resource degradation, so it is essential to conserve sufficient tree systems in all their various forms and layouts.

Line-plantings are a source of great biological richness for ecological preservation, bio conservation, water purification, and storm protection. Trees growing outside forests in line-plantings, clumps or woodlots have a special role in conservation-oriented water, biomass and soil fertility management. Where properly established, tree plantings tend to replace more mechanical approaches to soil and water protection, conservation and restoration.

Trees outside forests, regenerating spontaneously and/or planted to maintain or extend tree cover, are of great benefit in watershed management, reducing soil degradation and controlling desertification. The rivers and streams of mountainous zones and their ecosystems are protected by streamside trees and those growing on farmland. The 1992 UNCED stressed that mountains are a major reservoir of water, energy and biological diversity, and that mountain environments are essential to the survival of world ecosystems.

4.1.3.2 Biological diversity

No country can afford to ignore its phytogenetic resource base and at the same time expect to sustainably increase food supplies and address the issue of the environment, including climate change. Generations of farmers have given local communities an important role in the conservation and enhancement of these now seriously endangered resources (Leipzig Declaration, 1996). The greatest threat to the maintenance and sustainable development of genetic resources is posed by the overexploitation of natural resources. The risk that tree species or populations may vanish is aggravated by recurrent bouts of drought. Species vary in their ability to withstand these attacks. Species such as *Acacia nilotica*, *Pterocarpus lucens, Sclerocarya birrea, Prosopis africana, Lannea microcarpa* and *Dalbergia melanoxylon* are extremely sensitive to the impact of climate (FAO, 2001). An estimated 100 000 ha of savannah are lost every year in Cameroon and Senegal.

There are two strategies for protecting these assets (Secretariat of the Convention on Biological Diversity, 2000). One is ex situ conservation in botanical gardens, arboretums, and conservation stands. In this context, genetic improvement and breeding programmes in the Sahel are already holding out serious promise for the future of Anacardium occidental and Faidherbia albida (Leipzig Declaration, 1996). The other strategy is in situ conservation, where farmers draw upon their knowledge of the interactions between the environment, genetic resources and their own management practices to protect biological diversity. Home gardens in many countries offer refuges for certain rare plant and tree species contributing to the biological spectrum .This is also true of agroforests, with their high densities and great range of woody and non-woody species, which render environmental services comparable to those of the forest.

4.1.3.3 Climate and CO_2

Trees act as both sink and potential sources of carbon. The role of forest ecosystems in carbon storage is well known in the global context of the biosphere, in the regulation of atmospheric carbon, and in the reduction of greenhouse gases. The quantification of carbon sources and sinks and of wastes due to human activities is currently a major concern of the scientific community. Changes in land use, especially slash-and-burn practices and the resultant deforestation of tropical forest, are now responsible for some 20 percent of CO_2 emissions (FAO, 2010). According to the Intergovernmental Panel on Climate Change (IPCC), carbon fixation from reduced deforestation, forest regeneration, and intensified planting and agroforestry practices would amount to the equivalent of 12-15 percent of CO_2 emissions from fossil fuels from 1995-2050 (FAO, 2010).

The impact of Trees outside forests on reducing deforestation, stabilizing soils and ecosystems and sequestering carbon will become increasingly meaningful.

One item on the agenda of the 1997 Eleventh World Forestry Congress in Antalya, Turkey, was the expansion of carbon sinks by "the establishment of plantations on non-forested land, (...), the increase of forest cover on farmland or pasture through agroforestry systems" (Brown, 1997). Unruh *et al* (1993) estimated the amount of stored carbon in aboveground and underground biomass in 21 different agroforestry systems in subsahelian regions, concluding that the environmental role of agroforestry in terms of retaining organic matter in the soil and reducing deforestation (and thereby reducing

CO_2 emissions) is more important than its straightforward effect of carbon sequestration. Planting trees in non-forest areas as part of integrated land management efforts could help maintain stored carbon at acceptable levels.

However, much of the thinking on how Trees outside forests relate to climate regulation is still at the research stage, therefore resources should accordingly be mobilized to assess the importance of Trees outside forests within the carbon cycle.

Consideration of the beneficial impact of Trees outside forests, particularly in terms of development issues such as enhanced food security, poverty reduction and ecosystem conservation has highlighted the critical need for hard and fast facts and figures to reliably underpin promotion and support policies for Trees outside forests. These data could also help to carefully monitor the changing patterns and dynamics of this valuable but still largely underestimated resource.

5. Thesis framework

Although the importance of TOF is widely recognized, what is known until now about these forest formations is still limited, especially on large areas (Kleinn et al., 2001).

Few researches have been devoted to sampling strategies suitable for surveying small woodlots and tree rows. Probably, most of the results concerning these surveys are not published nor are they accessible. Examples of surveys performed by means of probabilistic sampling are due to Holmgren et al. (1994) in Kenya and Tokola (2006) in India. Both these surveys adopt classical two-phase sampling schemes, with aerial photos used in the first phase and field measurements in the second. Alternatively, Corona and Fattorini (2006) propose a two-stage scheme for surveying tree rows in a region of Central Italy. All the above-mentioned surveys were performed for specific assessments, while, at least to my knowledge, no attempt has been made to achieve well-behaved estimators of small woodlots and tree row attributes in the framework of multipurpose large-scale inventories.

In the same way, few researches have been devoted to sampling strategies suitable for scattered trees outside forest inventory. For instance, a systematic sampling design with plots clustered at each point has been proposed by Saket et al (2010) for scattered trees assessment in the framework of national forest monitoring of developing countries, while a two-phase sampling strategy has been proposed in United States with a first phase based on aerial photos and a second phase involving measurements in the field (Lister et al. 2009). However, these papers do not report any results about the statistical properties of the proposed strategies.

On extra-European level, an up-to-date monitoring system of TOF has been developed in Ghana (Asamoah-Boateng, 2003) and in India (Rathore & Prasad, 2002), where these formations represent one of the main resources of fuelwood for local rural populations. Besides these examples, it is adequate to report the Project TROF (Tree Resources Outside Forests) of the European Commission (Kleinn & Morales, 2002), concerning some countries of Latin America (Costa Rica, Guatemala and Honduras) and a series of pilot studies carried out by FAO in several countries as Mali, Namibia, Kenya, Morocco and Sudan with the aim of quantifying TOF and their economic and ecological importance (Bellefontaine et al., 2002).

On European level, the inventories of TOF on a national scale are limited to those conducted in the United Kingdom and in France. The United Kingdom has an old tradition in management of green areas, tree rows and rural hedges in agroforestry systems. In 2000, the fourth UK National Inventory of TOF has been completed after those of 1951, 1965 and 1979-82 (Wong, 2001). Besides this investigation, named Small Woods and Trees Inventory, integrated into the UK National Forest Inventory, also the Countryside Survey, activated in 1978 and reached its fourth repetition in 2000, provides data on tree row systems. In France, the TOF Inventory has detected tree row systems with the so-called associated strips method. This method analyses all tree rows located at a maximum distance of 25 m from the sampling point, providing an estimate of the total length of those formations (Bellefontaine et al., 2002).

In Italy, the second Italian National Forest Inventory (INFC – National Inventory of Forests and of Carbon Forest Sink) in the first phase of the survey, through aerial photo interpretation, provided the location of all points falling on forest linear formations and on small woodlots. On the basis of these data, a specific inventory for the territorial extension of TOF has been conducted in central Italy, with particular regard to 4 regions (Lazio, Marche, Tuscany, Umbria; Paletto et al., 2006).

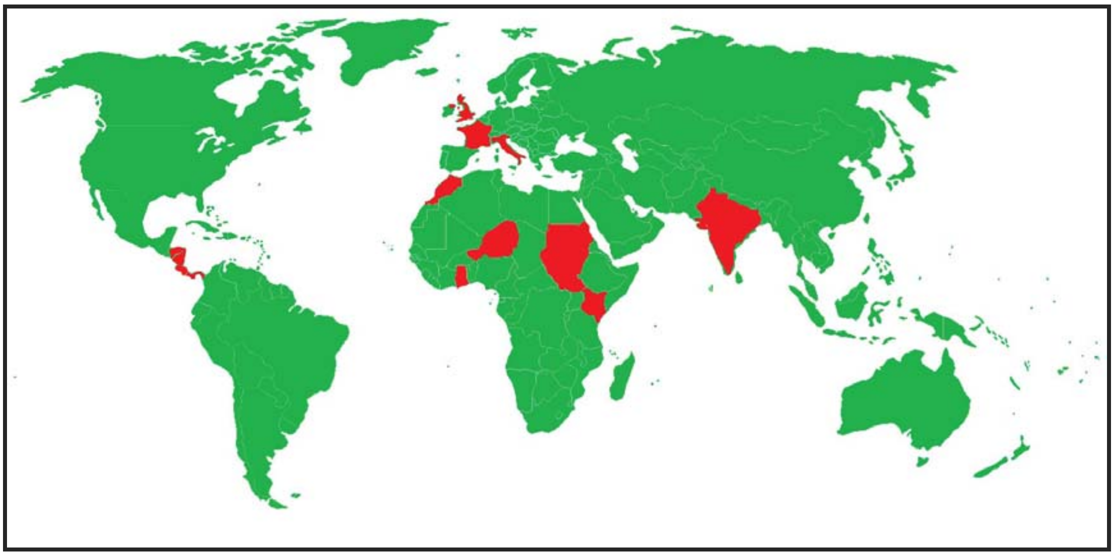


FIGURE 4: SCATTERED AND UNSYSTEMATIC EXISTING INFORMATION ABOUT TOF IN THE WORLD.

In this framework, the research-question to what this thesis wants to provide answer is to investigate the possibility of developing a sampling strategy suitable for surveying

TOF and widely applicable on large areas, in order to allow a more comprehensive knowledge of the quantitative and qualitative amount of all those valuable off-forest tree resources.

The main challenge of this research was to develop a methodology for inventory TOF which permit a straightforward, feasible implementation, exploiting the already existing network of large-scale forest inventories. Most inventories performed over large scale involve several phases of sampling and in particular the first-phase points, overlapped on aerial orthophotos or VHR satellite images, can be adopted and easily exploited to sample TOF and allow the building up of large-scale methodology for TOF inventory.

6. Developing a large-scale TOF inventory protocol

The main objective of TOF inventories is the estimation of population parameters such as the total number of units, the total surface, the volume of epigeal tree biomass and the carbon stocked in the biomass of small woodlots, tree-rows and scattered trees in non-forest areas.

The inventory of TOF is distinguished from a conventional forest inventory by the different structure of the specific elements to be inventoried: density of tree can be highly variable outside forest and trees can have very variable growth conditions in terms of inter-individual competition with effects also on stem and tree shape such that it can invalidates the usually applied volume and biomass functions. For these reasons, an efficient solution for local small-area TOF inventory could probably require the use of ad hoc sampling scheme. However, in order to save time and resources, it may be appealing to survey small woodlots, tree rows and scattered trees in the framework of already existing network of large-scale inventories.

Most inventories performed over very large scale (e.g. national inventories) involve several phases of sampling (Corona, 2000). The first phase is usually carried out by means of a systematic search of the study region, in which the region is partitioned into squares or other regular polygons of the same size and points are randomly or systematically selected, one per polygon. In most cases, the layout of the first-phase points can be overlapped on aerial orthophotos or very high resolution satellite images available for the whole study area (e.g. Fattorini et al. 2006; Opsomer et al. 2007) and each point can be recognized and classified.

Thus, the first phase of conventional large-areas inventories can be effectively adopted to sample TOF units. Small woodlots and tree rows, are simply selected if they contain at least one of the first-phase points and then their sizes and other physical attributes are directly measured on aerial orthophotos. Scattered trees are included in the sample if they fall within a pre-determintaed fixed circular area, centred on the survey points.

6.1 Reference standards

As it has been already remarked in previous paragraphs, it is of relevant importance to adopt a common and widespread system of classification of the elements to be inventoried. For this reason, in the case of this study, the assumed nomenclature scheme for the inventory of TOF refers to the definitions employed in the framework of the Italian National Forestry Inventory (INFC, 2003). The definition adopted for each TOF element is reported in paragraph 3.3.

6.2 Estimation of the attributes of small woodlots and tree rows

The assessment of the attributes of small woodlots and tree rows exploiting the first phase of large-scale multiphase forest inventories is carried out by means of an estimator of population totals which may be viewed as an approximation of both the Horvitz-Thompson (HT) and Hansen-Hurvitz (HH) estimators and which has the practical advantage of avoiding the cumbersome quantification of the first-order inclusion probabilities. Estimators of population averages are subsequently derived together with the estimator of the sampling variances.

6.2.1 Proposed sampling scheme and estimators

Let U be a population of N small woodlots or tree rows, say $a_1,\ldots,a_N$ in a delineated study area $\mathcal{A}$ of size $|\mathcal{A}|$. Denote by $|a_j|$ the size of unit j and by y_j the value of a physical attribute such as length (in the case of tree rows) measurable from orthophotos. Finally, suppose that the population total

$$T = \sum_{j \in \mathrm{U}} y_j$$

and the population mean $\bar{Y} = T / N$ are the interest quantities to be estimated. Then a set of n point is selected in accordance with a spatial sampling scheme and a unit enters the sample if at least one of the n sample points falls inside such unit.

Gregoire and Valentine (2008, chapter 10) provide an excellent introductory chapter on the issue of sampling discrete objects scattered on a region by means of plots, lines or points (as in the present case). The authors emphasize as these designs may also be conveniently re-formulated as spatial designs for sampling the continuous populations of points constituting the study area, also giving a list of references from the early 90's in which such intuition has been firstly developed. In this setting, the interest parameter T can be expressed as an integral over the study area and the spatial design for selecting the n points may be viewed as a two-dimensional Monte Carlo integration, thus focusing on the problem of how effectively select these points (see Appendix 2).

Despite of its simplicity, the completely random placement of sample points may lead to an uneven coverage of the study area. As pointed out by Cordy and Thompson (1995) and Stevens (2006), the so-called uniform random sampling may be unsatisfactory since some sub-regions may be sparsely sampled whereas others intensively. To avoid uneven coverage of the study area, systematic schemes can be adopted. However, the pure systematic sampling based on a regular grid of points with a random start (commonly adopted in stereology and in large-scale forest inventories, see e.g. Baddeley and Jensen, 2004 and Opsomer et al, 2007) may be unsuitable in presence of some spatial regularity, leading to heavy losses of efficiency. Accordingly, random systematic schemes based on a regular tessellation of the study area and the random placement of points in each tessellation units should be preferred. One such scheme, usually referred to as the tessellation stratified sampling (Cordy and Thompson, 1995, Stevens 1997) involves covering the study area $\mathcal{A}$ by a region, say $\mathcal{R} \supset \mathcal{A}$, of size $|\mathcal{R}|$ and constituted by n non-overlapping polygons $Q_1,\ldots,Q_n$ of equal size and such that $Q_i \cap \mathcal{A} \neq \varnothing$ for all $i = 1,2,\ldots,n$ and then selecting a point in each of these polygons. The scheme has a long standing in statistical literature (see e.g. Overton and Stehman, 1993); more recently it has been incorrectly labelled by United States Environmental Protection Agency (EPA) as the unaligned systematic sampling (see EPA 2002, p.63) despite of the differences with the genuine unaligned systematic scheme, originally proposed by Cochran (1977, p.228).

As proven in Appendix 1, if the study area can be exactly tessellated by polygons, the HH estimator under the tessellation stratified sampling turns out to be invariably more efficient than the same estimator under the uniform random sampling. This result was already derived, mutatis mutandi, in Monte Carlo integration (see e.g. Haber, 1966) but it does not hold when the study areas have irregular shapes, owing to the necessity of introducing an enlarged covering region $\mathcal{R}$ to perform the tessellation stratified scheme (see Appendix 2). However, under the tessellation stratified scheme the HH estimator display a variance of order $n^{-\alpha}$, with $1<\alpha\leq 3$ (Barabesi, 2003, Barabesi and Marcheselli 2003, 2008) while the same estimator under the uniform random sampling solely possesses a variance of order n^{-1}. Accordingly, for large n, the tessellation stratified scheme provides highly efficient estimators with relevant gains in precision with respect to the uniform random scheme.

Now, denote by S the set of distinct units selected at least once by the n points and let m be the cardinality of S. As proven in Appendix 3, under the tessellation stratified scheme the quantity

$$\widetilde{T}_n = \frac{|\mathcal{R}|}{n}\sum_{j\in S}\frac{y_j}{|a_j|} \tag{1}$$

may be viewed as an approximation of both the HT and HH estimators and as such it turns out to be approximately unbiased. It is worth noting that (1) avoids the cumbersome quantification of the sizes of the portions of the selected units lying in adjacent quadrats, as would be requested by the HT estimator (see Appendix 3). Moreover, as proven in Appendix 4, a conservative estimator for the variance of $\widetilde{T}_n$ is given by

$$\widetilde{V}^2_{(Y)n} = \frac{1}{n(n-1)}\left\{|\mathcal{R}|^2\sum_{j\in S}\left(\frac{y_j}{|a_j|}\right)^2 - n\widetilde{T}_n^2\right\} \tag{2}$$

while $\widetilde{T}_n \pm 1.96\widetilde{V}_{(Y)n}$ provides a confidence interval with nominal coverage equal to 95%.

If $y_j=1$ for each $j=1,\ldots,N$, the population total coincides with the population size N (henceforth referred to as the abundance) and (1) reduces to

$$\widetilde{N}_n = \frac{|\mathcal{R}|}{n}\sum_{j\in S}\frac{1}{|a_j|}$$

which provides an approximately unbiased estimator of N. From (2), the variance estimator reduces to

$$\widetilde{V}^2_{(N)n} = \frac{1}{n(n-1)}\left\{|\mathcal{R}|^2\sum_{j\in S}\frac{1}{|a_j|^2} - n\widetilde{N}_n^2\right\}$$

with a nominal 95% confidence interval $\widetilde{N}_n \pm 1.96\widetilde{V}_{(N)n}$.

If $y_j = |a_j|$ for each $j = 1,\ldots,N$, the population total coincides with the total area of the population units (henceforth referred to as the coverage and denoted by A). In this case (1) reduces to

$$\tilde{A}_n = \frac{|\mathcal{R}|m}{n}$$

which is the familiar coverage estimator commonly adopted in forest studies. If the n sample points are selected over the study area with equal inclusion density (as in the present case), the estimator turns out to be unbiased without any use of the inclusion probabilities (see e.g. De Vries, 1986, Chapter 10). From (2), the variance estimator reduces to

$$\tilde{V}^2_{(A)n} = \frac{|\mathcal{R}|^2 m(n-m)}{n^2(n-1)}$$

with a nominal 95% confidence interval $\tilde{A}_n \pm 1.96\tilde{V}_{(A)n}$.

In order to estimate the population mean $\bar{Y} = T/N$, a very natural procedure is to estimate T and N as well and then take the ratio

$$\tilde{\tilde{Y}}_n = \frac{\tilde{T}_n}{\tilde{N}_n} = \sum_{j \in S} \frac{y_j}{|a_j|} \Big/ \sum_{j \in S} \frac{1}{|a_j|} \qquad (3)$$

as the estimator of $\bar{Y}$. From the results of Appendix 5, (3) turns out to be approximately unbiased with variance estimator

$$\tilde{V}^2_{(\bar{Y})n} = \frac{|\mathcal{R}|^2}{\tilde{N}_n^2 n(n-1)} \sum_{j \in S} \left(\frac{y_j - \tilde{\tilde{Y}}_n}{|a_j|} \right)^2 \qquad (4)$$

and a nominal 95% confidence interval $\tilde{\tilde{Y}}_n \pm 1.96\tilde{V}_{(\bar{Y})n}$. If $y_j = |a_j|$ for each $j = 1,\ldots,N$, the estimator of the average size of the units reduces to

$$\tilde{\tilde{A}}_n = m \Big/ \sum_{j \in S} \frac{1}{|a_j|}$$

(i.e. the harmonic mean of the sampled $|a_j|$s), while the variance estimator reduces to

$$\tilde{V}^2_{(\bar{A})n} = \frac{|\mathcal{R}|^2}{\tilde{N}_n^2 n(n-1)} \sum_{j \in S} \left(1 - \frac{\tilde{\bar{A}}_n}{|a_j|} \right)^2$$

with a nominal 95% confidence interval $\tilde{\bar{A}}_n \pm 1.96 \tilde{V}_{(\bar{A})n}$.

6.2.2 Simulation study

6.2.2.1 Dataset

The performance of the estimators proposed in the previous section was checked by means of a simulation study performed on a set of artificial populations of small woodlots and tree rows. In order to make some reference to reality, the density and the size of the woodlots and tree rows roughly resembled the results of some real assessments performed in Italy.

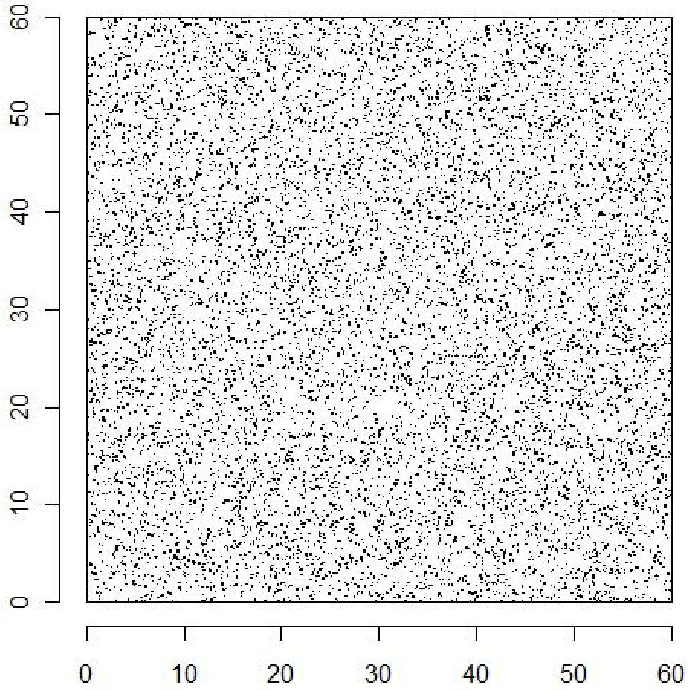
A quadrat of size $360{,}000 ha$ (side 60 km) was taken as the study area $\mathcal{A}$. Within the area, a population of $N = 10{,}000$ woodlots (density of about 2.8 woodlots per 100 ha) was plotted. For computational simplicity, the woodlots were presumed to be rectangularly-shaped with sides having the same orientation as the sides of the study area. In order to consider several spatial patterns, the N woodlot centers were distributed over the area: a) completely at random; b) in accordance to a clustered process in which 10 cluster centers were randomly distributed over the area and for each cluster center 1,000 woodlots centers were generated from a bivariate normal distribution centered at the cluster center and having independent marginals with standard deviation 5 km; c) in accordance with a spatially-trended process in which the coordinates of the cluster centers are independent random variables of type $(1-U^2)\times 60$ with U uniformly distributed on $(0,1)$. Woodlot centers falling outside the study area were discarded. Once the cluster centers were plotted, a rectangular woodlot was generated around each centre with both sides independently generated from a normal distribution with expectation $44 m$ and standard deviation $8 m$, in such a way to have woodlots with an expected size of about $0.2 ha$. Woodlots greater than $0.5 ha$ or partially lying outside the study area or overlapping previously-generated woodlots were discarded.

In an analogous way, a population of $N = 30{,}000$ tree rows (density of about 8.3 tree rows per 100 ha) was plotted. Also in this case, tree rows were rectangularly-shaped with the same orientation as the square sides, while their centers were distributed over the area in accordance with the three spatial patterns adopted for woodlots, with the only difference that in the case of the cluster process, there were 30 clusters of 1,000 tree lines and the coordinate centers around the cluster centers had standard deviation of 1.67 km instead of 5 km. Rectangular tree rows were constructed around their centers with lengths and widths independently generated from two normal distributions with expectations of $100m$ and $10m$ and standard deviations of $18m$ and $1.8m$, respectively, in such a way to have tree rows with an expected size of about $0.1ha$. Tree rows shorter than 20 m, wider than 20 m, partially lying outside the study area or overlapping previously-generated tree rows were discarded.

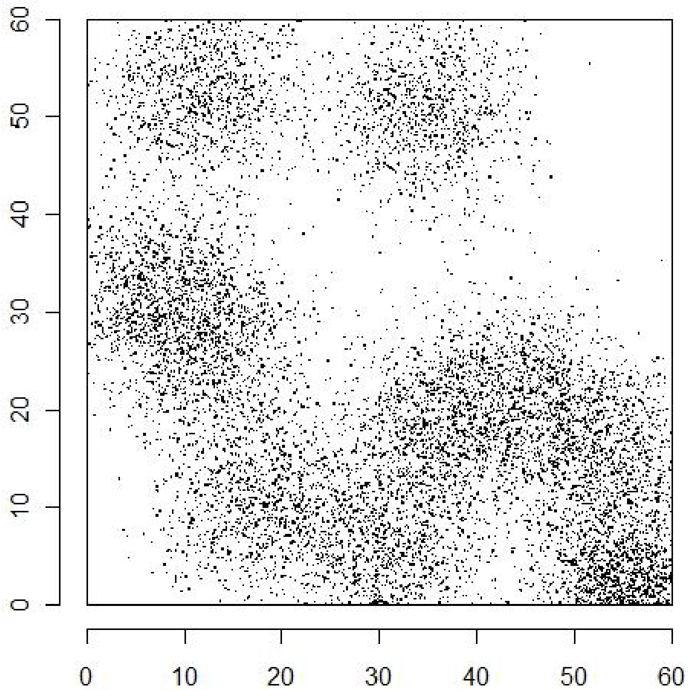
Figure 5 and Figure 6 plot the spatial distribution of the woodlots and tree rows arising from the spatial patterns of type a), b) and c).

FIGURE 5: SPATIAL DISTRIBUTIONS OF WOODLOT POPULATIONS ARTIFICIALLY GENERATED FROM RANDOM, CLUSTERED AND TRENDED SPATIAL PATTERNS.

A) RANDOM



B) CLUSTERED



C) TRENDED

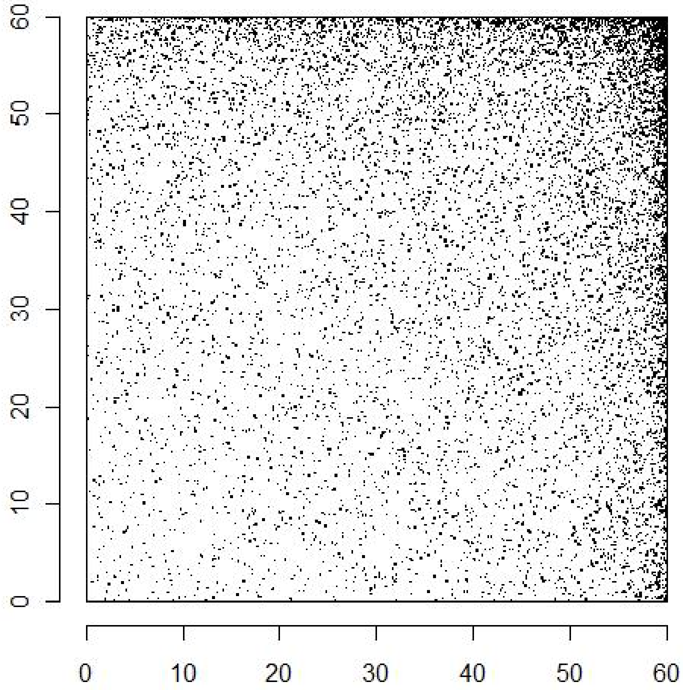
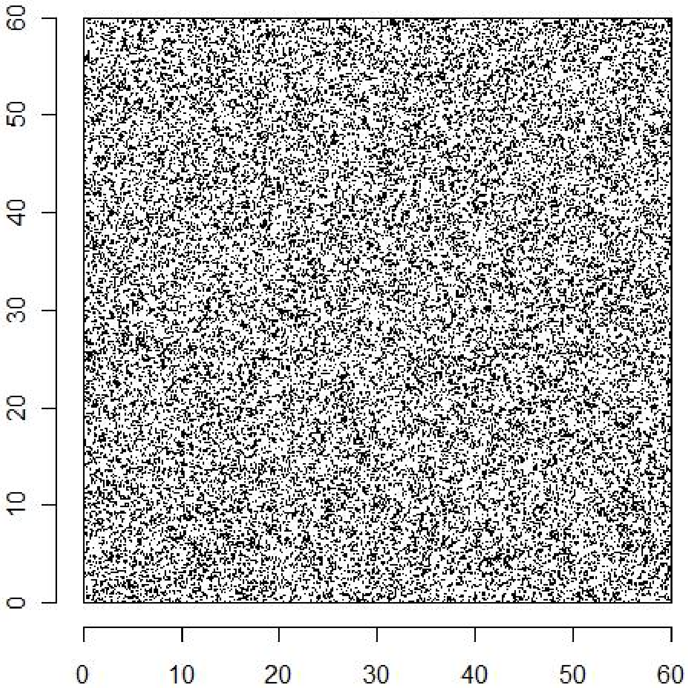
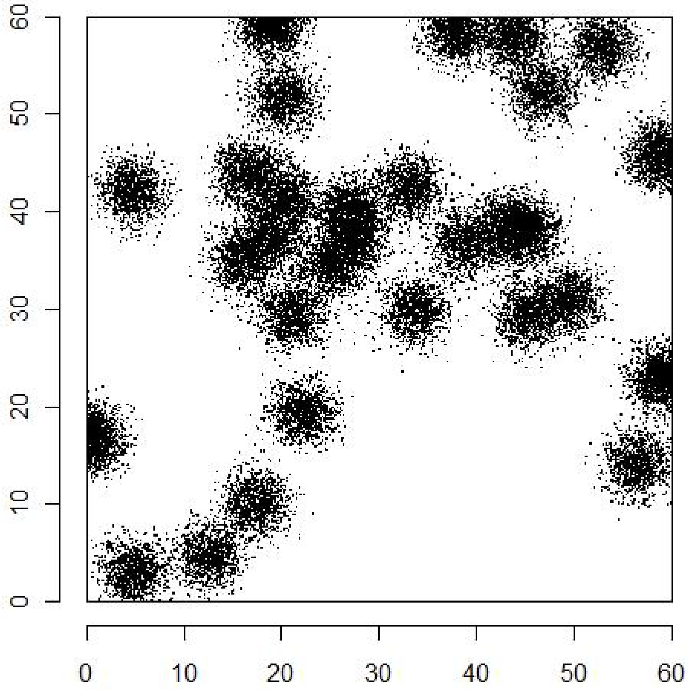


FIGURE 6: SPATIAL DISTRIBUTIONS OF TREE ROW POPULATIONS ARTIFICIALLY GENERATED FROM RANDOM, CLUSTERED AND TRENDED SPATIAL PATTERNS.

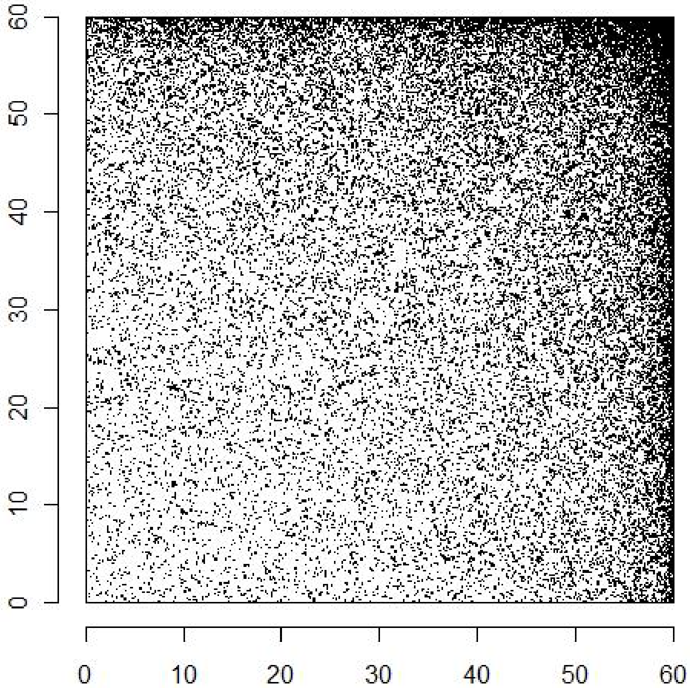
A) RANDOM



B) CLUSTERED



C) TRENDED



6.2.2.2 Sampling simulation

To simulate unaligned systematic sampling, the study area was partitioned into n=3.600 quadrats of size 100 ha (thus leading to a sampling intensity of the same order as that usually adopted by large-scale forest inventories like INFC). Then, for each spatial pattern, the first- and second-order inclusion probabilities of each woodlot or tree row were computed. For those units completely lying in a sole quadrat (single-quadrat units), which in all the populations constituted a percent of about 90% (see the last but one line of Tale 4 and Table 5), the computation was trivial. On the other hand, for the remaining 10% of units extending into adjacent quadrats, the computation needed for the sizes of the intersections of these units with such quadrats (see Appendix 3 the expression A6), while the expression of the second-order probabilities, even if straightforward, is huge and is not reported for the sake of brevity.

Obviously, the sum of the first-order inclusion probabilities provided the expectation for the size m of the samples arising from the unaligned systematic sampling.

Ten thousand samples of woodlots or tree rows were randomly generated. Each sample was generated by randomly selecting a point in each quadrat and including in the sample all the woodlots or tree rows containing at least one of these 3,600 points. As expected, in all the cases, the average percent of single-quadrats units in the sample turned out to be of about 90% as in the corresponding populations (see the last line of Table 4 and Table 5). For each simulated sample S, the abundance estimate, coverage estimate and average size estimate were computed by using the estimator of type (1). The coverage estimate and average size estimate were also computed by using the HT estimator. Furthermore, in the case of tree row populations, the total length estimate and the average length estimate were computed by using both type (1) and HT estimators. For each estimate of type (1), the corresponding estimate of the sampling variance was computed, which in turn gave rise to: i) an estimate of the relative standard error (RSE), obtained as the ratio of the square root of the variance estimate to the parameter estimate; ii) the confidence interval at the nominal level of 95% given by the parameter estimate plus and minus 1.96 times the square root of the variance estimate.

6.2.2.3 Performance indicators

The knowledge of the first- and second-order probabilities allowed for the exact computation of the relative bias (RB) and of the relative root mean squared error (RRMSE) of the estimator of type (1) as well as of the RRMSE of the HT estimator for abundance, coverage and total length. Indeed, both HT and type (1) estimators constitute linear homogeneous estimators (e.g Hedayat and Sinha, 1991, p.23). As such, the variance of the HT estimator is given by

$$V(\hat{T}_{HT}) = \sum_{j \in U} y_j^2 \frac{1-\pi_j}{\pi_j} + 2 \sum_{h > j \in U} y_j y_h \frac{\pi_{jh} - \pi_j \pi_h}{\pi_j \pi_h}$$

while expectation and variance of the type (1) estimator are given by

$$E(\tilde{T}_n) = \frac{|\mathcal{R}|}{n} \sum_{j \in U} y_j \frac{\pi_j}{|a_j|}$$

and

$$V(\tilde{T}_n) = \frac{|\mathcal{R}|^2}{N^2} \left\{ \sum_{j \in U} y_j^2 \frac{\pi_j (1-\pi_j)}{|a_j|^2} + 2 \sum_{h > j \in U} y_j y_h \frac{\pi_{jh} - \pi_j \pi_h}{|a_j||a_h|} \right\}$$

respectively.

On the other hand, the estimators of population averages, being ratios of estimators of type (1) or HT estimators, cannot be handled analytically. In these cases, RB and RRMSE were determined empirically on the basis of their Monte Carlo distributions. As to the estimators of type (1), the Monte Carlo distributions were also used to determine the expectations of the RSE estimators (ERSEE) and the actual coverage of the 95% confidence intervals (AC95), empirically determined as the percentage of times the simulated intervals contained the true parameter value.

The simulated values for RB and RRMSE were computed even when the analytic values are available in order to be compared with the theoretical counterparts and provide confirmation on the reliability of simulation results.

6.2.2.4 Results

Table 4 and Table 5 report the percent values of RB, RRMSE, ERSEE and AC95 for each artificial population and each parameter together with the percent values of

RRMSE achieved by using the HT estimator. The values determined analytically by means of the first- and second-order inclusion probabilities are marked by an asterisk. The closeness between the values obtained from the Monte-Carlo distributions and their theoretical counterparts gives sufficient insights on the adequacy of the simulation study.

TABLE 4: PERFORMANCE OF APPROXIMATE HORVITZ-THOMPSON ESTIMATORS OF PHYSICAL ATTRIBUTES FOR 3 ARTIFICIAL POPULATIONS OF 10.000 WOODLOTS PLOTTED ON A STUDY AREA OF 360.000 HA IN ACCORDANCE WITH RANDOM, CLUSTERED AND TRENDED SPATIAL DISTRIBUTION. VALUES IN BRACKET REFER TO THE HORVITZ-THOMPSON ESTIMATOR.

Parameter		UNIFORM		CLUSTERED		TRENDED	
Abundance	RB(%)*	0		0		0	
	RB(%)	-0.11		0.17		0.07	
	RRMSE(%)*	23.51	(23.51)	23.45	(23.45)	23.42	(23.42)
	RRMSE(%)	23.51		23.39		23.23	
	ERSEE(%)	23.95		23.91		23.97	
	AC95(%)	93.6		93.79		94.02	
Coverage	RB(%)*	0		0		0	
	RB(%)	-0.04		0.11		-0.05	
	RRMSE(%)*	22.65	(22.65)	22.59	(22.59)	22.56	(22.56)
	RRMSE(%)	22.61		22.50		22.50	
	ERSEE(%)	23.16		23.12		23.17	
	AC95(%)	94.01		94.21		94.3	
Average size	RB(%)	0.5		0.35		0.26	
	RRMSE(%)	6.4	(6.38)	6.45	(6.44)	6.46	(6.46)
	ERSEE(%)	5.98		5.95		5.97	
	AC95%	91.97		91.83		91.59	
Expected sample size* Expected sample size		19.34 19.34		19.36 19.38		19.31 19.30	
Single-quadrat woodlots: in the population (%) expected in the sample (%)		91.86 91.71		91.58 91.30		91.72 91.61	

(*) values determined analytically

TABLE 5: PERFORMANCE OF APPROXIMATE HORVITZ-THOMPSON ESTIMATORS OF PHYSICAL ATTRIBUTES FOR 3 ARTIFICIAL POPULATIONS OF 30,000 TREE ROWS PLOTTED ON A STUDY AREA OF 360,000 HA IN ACCORDANCE WITH RANDOM, CLUSTERED AND TRENDED SPATIAL DISTRIBUTION. VALUES IN BRACKETS REFER TO THE HORVITZ-THOMPSON ESTIMATOR.

Parameter		UNIFORM		CLUSTER		TREND	
Abundance	RB(%)*	0		0		0	
	RB(%)	-0.06		0.07		-0.04	
	RRMSE(%)*	18.82	(18.82)	18.6	(18.60)	18.72	(18.72)
	RRMSE(%)	19.06		18.47		18.78	
	ERSEE(%)	19.05		19.04		19.03	
	AC95(%)	94.03		94.55		93.86	
Coverage	RB(%)*	0		0		0	
	RB(%)	-0.09		0.09		0.02	
	RRMSE(%)*	18.15	(18.15)	17.92	(17.92)	18.05	(18.05)
	RRMSE(%)	18.36		17.87		18.03	
	ERSEE(%)	18.41		18.39		18.39	
	AC95(%)	93.29		93.71		93.17	
Average size	RB(%)	0.24		0.27		0.33	
	RRMSE(%)	5.05	(5.04)	4.97	(4.97)	5.05	(5.04)
	ERSEE(%)	4.81		4.83		4.8	
	AC95(%)	92.73		93.32		92.75	
Total length	RB(%)*	0		0		0	
	RB(%)	-0.08		0.12		-0.04	
	RRMSE(%)*	18.48	(18.48)	18.26	(18.26)	18.39	(18.39)
	RRMSE(%)	18.68		18.15		18.36	
	ERSEE(%)	19.41		19.35		19.38	
	AC95(%)	94.21		94.64		94.04	
Average length	RB(%)	0.12		0.18		0.14	
	RRMSE(%)	3.57	(3.57)	3.58	(3.57)	3.54	(3.54)
	ERSEE(%)	3.41		3.43		3.42	
	AC95(%)	93.02		92.73		93.04	
Expected sample size*		30.07		30.03		30.07	
Expected sample size		30.05		30.06		30.08	
Single-quadrat tree rows:							
in the population (%)		89.15		89.23		89.55	
expected in the sample (%)		88.84		88.66		89.26	

(*) values determined analytically

Simulation results show that no detrimental effect is involved in the use of estimators of type (1), which instead have the practical advantage of avoiding the cumbersome quantification of the inclusion probabilities involved in the HT estimation. The relative bias of estimators of type (1) is negligible in all situations and always smaller than 0.5%, while the RRMSEs are practically identical to those achieved by the HT estimator. The RSE estimators turn out to be conservative estimators of RRMSEs when population totals are under estimation (abundance, coverage and total length). These results confirm the conservative nature of the variance estimator. On the other hand, moderate underestimation takes place for population averages (average size and length). As to the performance of confidence intervals, the actual coverage always results smaller than the nominal coverage of 95 %, even if in no case it turns out to be smaller than 91%. These discrepancies are mainly due to the tails of the actual distributions which turn out to be slightly heavier than those of the normal density. Obviously, the under-coverage is more marked in the case of population averages, owing to the additional effect due to the underestimation of the sampling variance. The estimation of averages gives rise to RRMSEs of about 3%-6% while the estimation of totals turns out to be less efficient with RRMSEs of about 18-24%. These accuracy levels seem however to be quite satisfactory if compared with the expected sampling fraction which turns out to be invariably smaller than 0.002.

The simulation was repeated by doubling both the population sizes. The results are not reported here for the sake of brevity. Substantial reductions of RRMSEs together with improvements in the coverage of confidence intervals are achieved at doubled densities. Finally it is worth noting that in presence of clustered and trended spatial patters the use of uniform random sampling will lead to much higher standard errors than those achieved in the case of random or uniform patterns. On the other hand the use of tessellation stratified sampling, ensuring an even coverage of the study area, mitigates these detrimental effects, with standard errors which turn out to be similar for all the spatial patterns.

From a practical point of view, the proposed strategy appears to be relatively easy to implement. The sampled woodlots and tree rows are delineated onto the remotely sensed imagery to determine their size and length (in the case of tree rows). Other attributes of interest can be derived from the delineation, such as perimeter length or some shape indexes (e.g size to perimeter length ratio).

6.3 Estimation of the attributes of the scattered trees outside forest

As already remarked in the previous paragraphs, the scattered trees outside forests (STOF) are here intended for the purposes of this inventory as all single discrete forest trees, or small groups of forest trees (less than 0.05 ha wide), within rural and urbanized areas and not classified as forest (FAO 2001), small woodlots (i.e. wooded land with an area larger than 0.05 ha and less than 0.5 ha) or tree rows (shelterbelts, windbreaks, river galleries and line features along property borders, roads, railways).

Inventorying involves obtaining quantitative and qualitative information about a resource. The main objective of STOF inventories is the estimation of population parameters such as the total number of STOF (abundance) and totals and averages of STOF biophysical attributes (e.g. biomass, CO_2 sequestration).

Most inventories performed over a large scale (e.g. national inventories) involve several phases of sampling. Next paragraphs deal with the theoretical and practical aspects of STOF inventorying using a three-phase sampling strategy. The first phase is performed by means of a systematic search over the area to be inventoried, in which the area is partitioned into regular polygons of the same size and points are randomly thrown, one per polygon. In the second phase, the land cover of first-phase points is classified by very-high-resolution remotely-sensed imagery available for the whole area and a sample of points is selected from each land cover stratum. Then, the number of STOF lying within plots of adequate size centred at each sampled point is recorded. Finally, in the third phase, a subsample of points is selected from the second-phase points of each stratum and the biophysical attributes of STOF within the plots are measured.

6.3.1 Proposed sampling scheme and estimators

Let U be a STOF population on a delineated area $\mathcal{A}$. Denote by y_j the value of a tree attribute such as above-ground biomass, wood volume or basal area for the j-th tree and suppose that the population abundance, say X, and the population total

$$T = \sum_{j \in U} y_j$$

are the interest quantities to be estimated.

Fattorini et al. (2006) propose a three-phase sampling strategy for estimating forest attributes on a large scale. In the first phase, in order to ensure even coverage of the study area, a stratified spatial scheme usually referred to as tessellation stratified sampling (TSS) is adopted (see e.g. Cordy and Thompson 1995, Stevens 1997). By using a TSS scheme, the area is covered by a region, say $\mathcal{R} \supset \mathcal{A}$ of size R and constituted by N non-overlapping regular polygons, say $Q_1,\ldots,Q_N$, of equal size and such that $Q_i \cap \mathcal{A} \neq \varnothing$ for all $i = 1,2,\ldots,N$. Then, for each polygon i, a point, say $\mathbf{p}_i$, is randomly thrown within the polygon, in such a way that a discrete population of N points, say $\mathsf{P} = \{\mathbf{p}_1,\ldots,\mathbf{p}_N\}$ is achieved.

If each point of P was visited on the ground and a plot of fixed size a was constructed around each point, then for each i-th point, a sample of STOF lying within the plot, say U_i, would be obtained. If the interest attribute Y was measured and recorded for all the STOF of U_i, then the Horvitz-Thompson estimator of T at i-th would turn out to be

$$\hat{T}_i = \frac{R}{a}\sum_{j \in \mathsf{U}_i} y_j \ , \ i = 1,\ldots,N$$

in such a way that the arithmetic mean

$$\hat{\hat{T}}_1 = \frac{1}{N}\sum_{i=1}^{N}\hat{T}_i \qquad (5)$$

would constitute a one-phase unbiased estimator for T (see e.g. Barabesi, 2003). Moreover, owing to the independence of the $\hat{T}_i$ s, the quantity

$$V_{1T}^2 = \frac{1}{N(N-1)}\sum_{i=1}^{N}(\hat{T}_i - \hat{\hat{T}}_1)^2 \qquad (6)$$

would constitute a conservative estimator of the sampling variance of (5) (e.g. Wolter 1985, Theorem 2.4.1). It is worth noting that some edge effects might be present owing to STOF positioned near the inner edge of the considered region, which will have inclusion probabilities smaller than a / R. A long list of correction methods has been proposed in order to avoid the negative bias induced by edge effects (see e.g. Gregoire and Valentine 2008, section 7.5). Fortunately, in this framework, TSS performs like the correction method usually referred to as the buffer method (e.g. Gregoire and Valentine 2008, section 7.5.1), which entails allowing sample points to fall outside the boundary of $\mathcal{A}$, but within some larger region that includes $\mathcal{A}$. Under TSS the presence of STOF in $\mathcal{A}$ whose inclusion zone overlaps the boundary of the enlarged region $\mathcal{R} \supset \mathcal{A}$ should become negligible. Thus, edge effects can be ignored throughout the paper with no detrimental effect on the bias of the estimators.

Unfortunately, owing to the costs and time involved, in real situations plot sampling cannot be performed for each first-phase point, but rather for a portion of these points selected in the second phase. Accordingly, the first-phase survey is only hypothetical and its treatment has had the sole aim of constructing the theoretical basis for the analysis of the subsequent phases. As suggested by Fattorini et al. (2006), in the second phase the population of first-phase points P is partitioned into L strata, say $\mathsf{P}_1,\ldots,\mathsf{P}_L$ of sizes $N_1,\ldots,N_L > 1$ and a sample of points, say $\mathsf{S}_l \subset \mathsf{U}_l$, of size $n_l \geq 2$ is selected from each stratum $l = 1,\ldots,L$ by means of simple random sampling without replacement (SRSWOR). Accordingly, if the plots corresponding to all the points selected in the second phase are visited, the quantity

$$\hat{\hat{T}}_2 = \sum_{l=1}^{L} w_l \hat{\hat{T}}_{2l} \qquad (7)$$

where $w_l = N_L / N$ and

$$\hat{\hat{T}}_{2l} = \frac{1}{n_l} \sum_{i \in \mathsf{S}_l} \hat{T}_i$$

constitutes the two-phase unbiased estimator of T. Moreover, quoting from Fattorini et al (2006, expression 4.2), a conservative and invariably-positive estimator of the sampling variance of (7) is given by

$$V_{2T}^2 = \frac{1}{N-1}\left\{\sum_{l=1}^{L} w_l (N_l - 1)\frac{s_{2lT}^2}{n_l} + \sum_{l=1}^{L} w_l (\overline{T}_{2l} - \overline{T}_2)^2\right\} \qquad (8)$$

where

$$s_{2lT}^2 = \frac{1}{n_l - 1} \sum_{i \in \mathsf{S}_l} (\hat{T}_i - \overline{T}_{2l})^2$$

Note that if $y_j = 1$ for each $j \in \mathsf{U}$, then T reduces to the population abundance X. In this case the $\hat{T}_i$s reduce to $\hat{X}_i = Rd_i$, where d_i denotes the STOF density within plot i.

Thus, from (7), the two-phase estimator of the population abundance, say $\hat{\hat{X}}_2$, reduces to

$$\hat{\hat{X}}_2 = \sum_{l=1}^{L} w_l \hat{\hat{X}}_{2l} \qquad (9)$$

where

$$\hat{\hat{X}}_{2l} = \frac{1}{n_l} \sum_{i \in \mathrm{S}_l} \hat{X}_i$$

Moreover, from (8), the conservative and invariably-positive estimator of the sampling variance of (9) reduces to

$$V_{2X}^2 = \frac{1}{N-1} \left\{ \sum_{l=1}^{L} w_l (N_l - 1) \frac{s_{2lX}^2}{n_l} + \sum_{l=1}^{L} w_l (\hat{\hat{X}}_{2l} - \hat{\hat{X}}_2)^2 \right\} \qquad (10)$$

where

$$s_{2lX}^2 = \frac{1}{n_l - 1} \sum_{i \in \mathrm{S}_l} (\hat{X}_i - \hat{\hat{X}}_{2l})^2$$

But once again, in most situations all the n second-phase points cannot be visited on the ground. Usually, only the number of STOF lying within the second-phase plots are recorded by remotely-sensed imagery, in such a way that only the two-phase estimate of abundance $\hat{\hat{X}}_2$ can be computed in the second phase. Accordingly, a third phase of sampling is necessary to estimate T. As suggested by Fattorini et al. (2006), a sample of points, say $\mathrm{G}_l \subset \mathrm{S}_l$, of size $m_l \geq 2$ is selected from each second-phase sample S_l by means of SRSWOR. Once the plots corresponding to all the points selected in the third phase are visited, the quantity

$$\hat{\hat{T}}_3 = \sum_{l=1}^{L} w_l \hat{\hat{T}}_{3l} \qquad (11)$$

where

$$\hat{\hat{T}}_{3l} = \frac{1}{m_l} \sum_{i \in \mathrm{G}_l} \hat{T}_i$$

constitutes the three-phase unbiased estimator of T. Moreover, quoting from Fattorini et al. (2006, expression 5.4), a conservative and invariably-positive estimator of the sampling variance of (11) is given by

$$V_{3T}^2 = \frac{1}{N-1}\left\{\sum_{l=1}^{L} w_l (N_l - 1)\frac{s_{3lT}^2}{m_l} + \sum_{l=1}^{L} w_l (\hat{\hat{T}}_{3l} - \hat{\hat{T}}_3)^2\right\} \tag{12}$$

where

$$s_{3lT}^2 = \frac{1}{m_l - 1}\sum_{i \in G_l} (\hat{T}_i - \hat{\hat{T}}_{3l})^2$$

Finally, in order to estimate the population mean $\bar{Y} = T / X$, a very natural procedure is to take the ratio

$$\hat{\hat{Y}} = \hat{\hat{T}}_3 / \hat{\hat{X}}_2 \tag{13}$$

as the estimator of $\bar{Y}$. From the results in Fattorini et al. (2006, section 6), estimators of type (13) turn out to be approximately unbiased with an approximately conservative variance estimator

$$V_{\bar{Y}}^2 = \frac{V_{3T}^2}{\hat{\hat{X}}_2^2} - 2\frac{\hat{\hat{T}}_3 C_{3XT}}{\hat{\hat{X}}_2^3} + \frac{\hat{\hat{T}}_3^2 V_{2X}^2}{\hat{\hat{X}}_2^4} \tag{14}$$

where C_{3XT} denotes the three-phase estimator for the covariance between $\hat{\hat{X}}_2$ and $\hat{\hat{T}}_2$, which is given by

$$C_{3XT} = \frac{1}{N-1}\left\{\sum_{l=1}^{L} w_l \frac{N_l - 1}{n_l - 1}\frac{1}{m_l}\sum_{i \in G_l} (\hat{X}_i - \hat{\hat{X}}_{2l})\hat{T}_i + \sum_{l=1}^{L} w_l (\hat{\hat{X}}_{2l} - \hat{\hat{X}}_2)(\hat{\hat{T}}_{3l} - \hat{\hat{T}}_3)\right\}$$

(see Fattorini et al., 2006, expression 5.3).

As to variance estimation, it is worth noting that while the estimators (10) and (12) are based on the actual theoretical variances of $\hat{\hat{X}}_2$ and $\hat{\hat{T}}_3$ and thus turn out to be invariably positive, estimator (14) is based on an approximate variance expression obtained via the first-order Taylor series approximation of the ratio $\hat{\hat{T}}_3 / \hat{\hat{X}}_2$ around the true population values T and X. For this reason, in some (although rare) situations, when $\hat{\hat{X}}_2$ and $\hat{\hat{T}}_3$ are highly dissimilar from their population counterparts (e.g. owing to inadequate sampling efforts), estimator (14) may be negative and must be discarded. In this case, a very practical solution is to neglect the covariance term in (14). Accordingly, an invariably positive estimator of (13) turns out to be

$$V_{\bar{Y}pos}^2 = \begin{cases} V_{\bar{Y}}^2 & if\ V_{\bar{Y}}^2 > 0 \\ \dfrac{V_{3T}^2}{\hat{X}_2^2} + \dfrac{\hat{T}_3^2 V_{2X}^2}{\hat{X}_2^4} & otherwise \end{cases} \tag{15}$$

6.3.2 Simulation study

6.3.2.1 Dataset

The performance of the strategy proposed in the previous section was checked by means of a simulation study performed on a set of artificial STOF populations. In order to make reference to reality, the density and the above-ground tree biomass (ATB) - which was considered as the interest attribute Y - of simulated populations roughly resembled the results of some real assessments.

A quadrat of size $62{,}500\,ha$ (side 25 km) was taken as the study area $\mathcal{A}$. The area is partitioned into $N = 625$ quadrats of size 100 ha. Since the target areas of real STOF surveys are mostly constituted by agricultural land (i.e. cropland and grassland where the presence of STOF is more likely), then $N_1 = 450$ contiguous quadrats out of 625 (72 %) located in the lower part of the study region were presumed to belong to Stratum 1 (agricultural land), while the remaining $N_2 = 175$ (28 %) were presumed to belong to Stratum 2 (other land). Moreover, overall densities of D = 50, 100, 150 STOF per 100 ha were presumed within the whole study area. Now, denote by D_1 and D_2 the STOF density within Strata 1 and 2, respectively. For each overall density D, two situations were presumed: i) $D_1 = D_2$; ii) $D_1 = 1.3D$. Obviously, in the second situation, the STOF densities of Stratum 1 corresponding to the overall densities D = 50, 100, 150 increased to D_1 = 65, 130, 195, respectively, while the STOF density of Stratum 2 decreased to D_2 = 11, 23, 34, respectively. Furthermore, in order to take into account the STOF distribution over the study area, a completely random distribution (RAND) was considered simply by assigning to each quadrat i of stratum l a STOF number, say x_i, randomly generated from a Poisson distribution with parameter D_l

($i = 1,\ldots,N_l$, $l = 1,2$). On the other hand, an aggregated spatial pattern (AGGR) was considered by generating x_i from a negative binomial distribution with parameters $k = D_l(1/p - p)$ and $p = 0.9375$ in such a way as to have an expectation equal to D_l and variance equal to $16D_l$. Even if the resulting population sizes varied among the twelve populations, they turned out to be of about $30{,}000$, $60{,}000$ and $90{,}000$ in accordance with the three values of D. Finally, for each generated STOF j , an ATB value y_j (t) was generated from a log-normal distribution with expectation and variance both equal to 0.3 (coefficient of variation 180%). Generated values greater than 8 t were discarded and substituted by new values.

For each combination of overall density, densities within strata and spatial pattern, a final set of twelve populations was available.Figure 7 and Figure 8 plot the resulting STOF populations in the case of random and aggregate patterns respectively, for $D_1 = 195$ and $D_2 = 34$.

FIGURE 7: SPATIAL DISTRIBUTIONS OF A STOF POPULATION ARTIFICIALLY GENERATED FROM A RANDOM SPATIAL PATTERN (RAND) OVER A QUADRAT OF SIZE 62,500 HA WITH OVERALL DENSITY OF 50 (TREES X 100 HA), AGRICULTURAL LAND DENSITY (WHITE) OF 65 AND OTHER LAND DENSITY (GREY) OF 11.

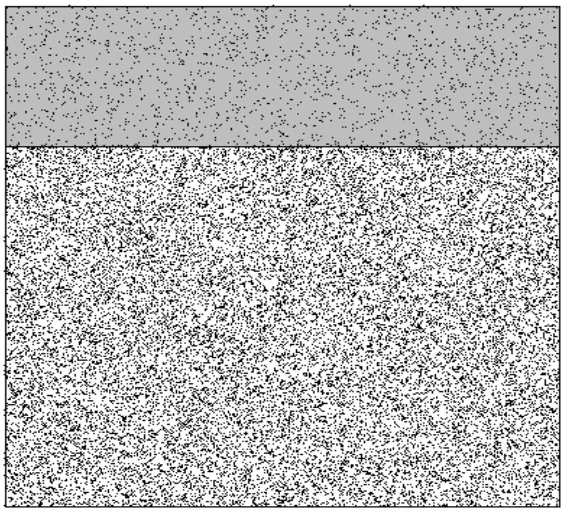
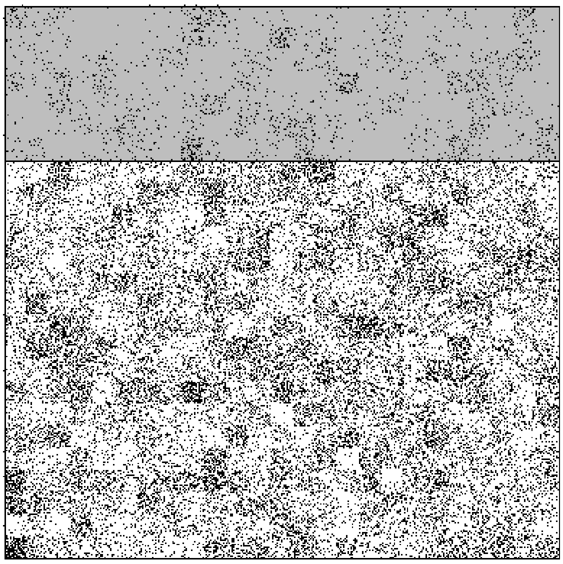


FIGURE 8: SPATIAL DISTRIBUTIONS OF A STOF POPULATION ARTIFICIALLY GENERATED FROM AN AGGREGATE SPATIAL PATTERN (AGGR) OVER A QUADRAT OF SIZE 62,500 HA WITH OVERALL DENSITY OF 50 (TREES X 100 HA), AGRICULTURAL LAND DENSITY (WHITE) OF 65 AND OTHER LAND DENSITY (GREY)



6.3.2.2 Sampling simulation

To simulate the three-phase sampling previously described, ten thousand samples of STOF were generated from each artificial population. In the first phase, in order to simulate TSS, a point is randomly selected within each quadrat. It is worth noting that the sampling intensity simulated in the first phase is similar to that usually adopted by national forest inventories, e.g. the Italian National Forest Inventory (see e.g. Fattorini et al. 2006, section 7, and the website http://www.infc.it).

In the second phase, the 625 points selected in the first phase were partitioned into Strata 1 and 2. Since each quadrat belonged to a unique stratum, Strata 1 and 2 were invariably constituted by $N_1 = 450$ and $N_2 = 175$ points. Then from each second-phase stratum U_1 and U_2 a fraction of about 5 and 10% of points were selected by means of simple random sampling without replacement (SRSWOR). More precisely, in the case of a 5% sampling fraction, $n_1 = 22$ and $n_2 = 9$ points were selected in the second phase, for a final two-phase sample size of $n = 31$, while under a 10% sampling fraction, the sizes turned out to be $n_1 = 45$, $n_2 = 18$ and $n = 63$. For each of the n points selected in the second phase a plot with a radius of 100 meters was centred at the point and the number of STOF lying within the plot was recorded. Then, the two-phase estimate of abundance and the estimate of its sampling variance were computed on the basis of expressions (9) and (10), respectively.

Subsequently, in the third phase, from each second-phase sample S_1 and S_2 a fraction of about 50% of points was selected by means of SRSWOR. More precisely, in the case of a 5% second-phase sampling fraction, the sizes turned out to be $m_1 = 11$ and $m_2 = 4$ for a final three-phase sample size of $m = 15$, while under a 10% second-phase sampling fraction the sizes were $m_1 = 22$, $m_2 = 9$ and $m = 31$. For each of the m points selected in the third phase, the ATB of each STOF lying within the corresponding plot with a radius of 100 meters was recorded and the three-phase estimate of the ATB total and the estimate of its sampling variance were computed on the basis of expressions (11) and (12), respectively. Moreover, the estimate of the average ATB per STOF and the estimate of its sampling variance were computed on the basis of expressions (13) and (15), respectively. Finally, the variance estimates were converted into estimates of relative standard error (RSE) simply by considering the ratio of the square root of the variance estimate to the corresponding parameter estimate.

6.3.2.3 Performance indicators

For each combination of artificial population and second-phase sampling effort (n = 31, 63), the sampling simulation provided the Monte Carlo distributions of the abundance estimates, total biomass estimates and average biomass estimates as well as the Monte Carlo distributions of the corresponding RSE estimates. From the Monte Carlo distributions of estimates, the relative bias (RB) and the relative root mean squared error (RRMSE) of estimators of type (9), (11) and (13) were empirically determined. Moreover, the Monte Carlo distributions of the RSE estimates were used to determine the expectation of the RSE estimators (ERSEE) obtained from variance estimators of type (10), (12) and (15) to be compared with the corresponding RRMSEs. As to (15), the number of times in which estimator (14) gave rise to negative values was also considered. Finally, the expected sampling efforts performed in the second and third phase in terms of sampled STOF (E2PSE and E3PSE) were determined by using the average proportion of the total number of STOF sampled in the second and third phase with respect to the population abundance. These quantities may be useful for comparing the performance of the estimators with respect to the simulated field work.

6.3.2.4 Results

Table 6 reports the percent values of E2PSE and E3PSE, while Table 7, Table 8 and Table 9, report the percent values of RB, RRMSE and ERSEE concerning the estimation of abundance (Table 7), total biomass (Table 8) and average biomass (Table 9) for each artificial population and each second-phase sampling effort.

The relative bias of estimators of type (9), (11) and (13) is invariably negative (owing to edge effects) but always negligible, being always smaller than 0.7 %. The RRMSEs of the two-phase estimator of abundance vary from about 5 to 15% and as such they are satisfactory compared with the average percentages of STOF sampled in the second phase, which are invariably equal to the 0.15-0.16% of the STOF population when 5% of plots are selected in the second phase, increasing to 0.31-0.32% under the selection of 10% of plots. A marked decrease in efficiency is induced by the third phase of sampling. The RRMSEs of the three-phase estimators of total and average ATB vary from about 20 to 40% in the presence of low densities (50 STOF per 100 ha), but decrease to about 15 to 20% in the presence of a density of 150 STOF per 100 ha.

The RSE estimator turns out to be a conservative estimator of RRMSEs when abundance is the target parameter. These results confirm the conservative nature of the variance estimator of type (10). On the other hand, moderate underestimation of variance and consequently of RSE takes place for the three-phase estimators of type (12) and (15). Underestimation reduces drastically as the plot sampling fraction of the second-phase increases from 5 to 10%. Moreover, as to estimator (14), a few dozens of negative values occur out of 10,000 when a plot sampling fraction of 5% is adopted in the second phase, owing to the presence of highly erroneous estimates of abundance and total ATB. The problem practically disappears under a plot sampling fraction of 10%, when more accurate estimates are achieved.

Finally, as expected, the presence of clustered spatial patterns causes reductions of efficiency in all the cases and for all the estimators. However, these reductions are always moderate owing to the use of TSS, which in the first phase ensures even coverage of the study area, but also owing to the stratifications performed in the subsequent phases which provide balanced samples with respect to the variation in STOF densities over the study area. More detrimental effects of aggregation might be expected if plots were selected completely at random over the area.

TABLE 6: AVERAGE PERCENTAGES OF THE TOTAL NUMBER OF STOF SAMPLED IN THE SECOND (E2PSE) AND THIRD PHASE (E3PSE) WITH RESPECT TO POPULATION ABUNDANCE FOR 12 ARTIFICIAL STOF POPULATIONS DISTRIBUTED OVER A STUDY AREA OF 62.500 HA.

Overall STOF density per km^2	STOF density in Stratum 1	STOF density in Stratum 2	Spatial pattern	Second-phase sample size	E2PSE	E3PSE
50	50	50	RAND	31	0.16%	0.08%
				63	0.32%	0.16%
			AGGR	31	0.16%	0.07%
				63	0.32%	0.15%
	65	11	RAND	31	0.15%	0.08%
				63	0.31%	0.15%
			AGGR	31	0.15%	0.08%
				63	0.31%	0.15%
100	100	100	RAND	31	0.16%	0.08%
				63	0.32%	0.16%
			AGGR	31	0.16%	0.08%
				63	0.32%	0.16%
	130	23	RAND	31	0.15%	0.08%
				63	0.31%	0.15%
			AGGR	31	0.15%	0.08%
				63	0.31%	0.15%
150	150	150	RAND	31	0.16%	0.08%
				63	0.32%	0.16%
			AGGR	31	0.16%	0.08%
				63	0.32%	0.16%
	195	34	RAND	31	0.15%	0.08%
				63	0.31%	0.15%
			AGGR	31	0.15%	0.08%
				63	0.31%	0.15%

TABLE 7: THE PERFORMANCE OF THE TWO-PHASE ESTIMATOR OF ABUNDANCE AND OF ITS VARIANCE ESTIMATOR FOR 12 ARTIFICIAL STOF POPULATIONS DISTRIBUTED OVER A STUDY AREA OF 62,500 HA (RB = RELATIVE BIAS; RRMSE = RELATIVE ROOT MEAN SQUARED ERROR; ERSEE = EXPECTATION OF THE RSE ESTIMATORS).

Overall STOF density per km^2	STOF density in Stratum 1	STOF density in Stratum 2	Spatial pattern	Second-phase sample size	RB	RRMSE	ERSEE
50	50	50	RAND	31	-0.32%	14.33%	14.37%
				63	-0.25%	10.02%	10.11%
			AGGR	31	-0.33%	17.03%	16.91%
				63	-0.27%	11.91%	11.93%
	65	11	RAND	31	-0.16%	14.65%	14.61%
				63	-0.21%	10.05%	10.31%
			AGGR	31	-0.18%	17.14%	17.27%
				63	-0.23%	11.96%	12.24%
100	100	100	RAND	31	-0.26%	10.22%	10.16%
				63	-0.32%	7.20%	7.14%
			AGGR	31	-0.21%	12.03%	12.02%
				63	-0.23%	8.37%	8.47%
	130	23	RAND	31	-0.41%	10.12%	10.40%
				63	-0.20%	7.07%	7.40%
			AGGR	31	-0.32%	12.08%	12.28%
				63	-0.11%	8.47%	8.74%
150	150	150	RAND	31	-0.25%	8.41%	8.30%
				63	-0.32%	5.84%	5.83%
			AGGR	31	-0.19%	9.79%	9.74%
				63	-0.34%	6.76%	6.87%
	195	34	RAND	31	-0.20%	8.41%	8.54%
				63	-0.15%	5.90%	6.17%
			AGGR	30	-0.16%	9.73%	9.99%
				63	-0.36%	6.85%	7.17%

TABLE 8: THE PERFORMANCE OF THE THREE-PHASE ESTIMATOR OF TOTAL ATB AND OF ITS VARIANCE ESTIMATOR FOR 12 ARTIFICIAL STOF POPULATIONS DISTRIBUTED OVER A STUDY AREA OF 62,500 HA (RB = RELATIVE BIAS; RRMSE = RELATIVE ROOT MEAN SQUARED ERROR; ERSEE = EXPECTATION OF THE RSE ESTIMATORS).

Overall STOF density per km^2	STOF density in Stratum 1	STOF density in Stratum 2	Spatial pattern	Second-phase sample size	RB	RRMSE	ERSEE
50	50	50	RAND	31	-0.69%	39.30%	34.30%
				63	-0.41%	27.01%	25.32%
			AGGR	31	0.12%	41.17%	36.18%
				63	-0.58%	28.02%	26.48%
	65	11	RAND	31	-0.02%	38.60%	34.17%
				63	-0.07%	27.50%	25.35%
			AGGR	31	-0.05%	40.79%	36.04%
				63	0.05%	28.57%	26.83%
100	100	100	RAND	31	-0.43%	28.24%	25.52%
				63	-0.38%	19.33%	18.53%
			AGGR	31	-0.29%	29.02%	27.01%
				63	0.11%	20.37%	19.59%
	130	23	RAND	31	-0.41%	27.50%	25.46%
				63	-0.25%	19.64%	18.71%
			AGGR	31	-0.21%	29.17%	26.91%
				63	-0.13%	20.63%	19.66%
150	150	150	RAND	31	-0.58%	22.68%	21.19%
				63	-0.34%	15.99%	15.29%
			AGGR	31	-0.26%	23.58%	22.33%
				63	-0.36%	16.42%	16.04%
	195	34	RAND	31	0.34%	22.58%	21.31%
				63	0.07%	16.31%	15.49%
			AGGR	31	0.11%	23.93%	22.44%
				63	-0.29%	16.78%	16.31%

TABLE 9: THE PERFORMANCE OF THE THREE-PHASE ESTIMATOR OF AVERAGE ATB AND OF ITS VARIANCE ESTIMATOR FOR 12 ARTIFICIAL STOF DISTRIBUTED OVER A STUDY AREA OF 62,500 HA (RB = RELATIVE BIAS; RRMSE = RELATIVE ROOT MEAN SQUARED ERROR; ERSEE = EXPECTATION OF THE RSE ESTIMATORS).

Overall STOF density per km^2	STOF density in Stratum 1	STOF density in Stratum 2	Spatial pattern	Second-phase sample size	RB	RRMSE	ERSEE
50	50	50	RAND	31	-0.45%	36.77%	31.19%
				63	-0.21%	25.02%	23.20%
			AGGR	31	0.48%	38.36%	32.19%
				63	-0.32%	25.57%	23.70%
	65	11	RAND	31	0.14%	36.17%	31.03%
				63	0.13%	25.69%	23.18%
			AGGR	31	0.07%	37.40%	31.80%
				63	0.31%	26.26%	23.94%
100	100	100	RAND	31	-0.23%	26.32%	23.43%
				63	-0.07%	17.93%	17.07%
			AGGR	31	-0.09%	26.57%	24.27%
				63	0.34%	18.69%	17.65%
	130	23	RAND	31	0.01%	25.92%	23.21%
				63	-0.05%	18.34%	17.17%
			AGGR	31	0.09%	26.75%	24.12%
				63	-0.02%	18.91%	17.64%
150	150	150	RAND	31	-0.34%	21.06%	19.52%
				63	-0.03%	14.88%	14.16%
			AGGR	31	-0.03%	21.81%	20.13%
				63	-0.02%	15.05%	14.50%
	195	34	RAND	31	0.55%	21.07%	19.50%
				63	0.22%	15.21%	14.19%
			AGGR	31	0.23%	21.75%	20.07%
				63	0.05%	15.28%	14.62%

6.4 Case study

To check the feasibility of the proposed procedures an experiment has been performed in five different units in various landscapes in Italy. The total area of the experimental surface is of about 355.000 ha (see Table 10) in which the proposed survey methodology to assess TOF in large territories, exploiting the first-phase of the large-scale multiphase forest inventories, has been tested.

The methodology has proved satisfactory and of valuable practical application, especially if compared to the sampling effort which has demonstrated to be rather limited. The methodology of sampling and survey, the operative protocol and the results coming from the application in the five areas of the case study are discussed below in the following paragraphs.

6.4.1 Methodology of sampling and survey

The study area has been identified on remote sensed images orthorectified and at high geometrical resolution. On the basis of this support, several survey points have been dislocated according to an unaligned systematic sampling. A such sampling scheme can be realized by the overlap on the territory under investigation of a grid with each quadrat having at least one portion of the territorial surface and by selecting a survey point by randomly in each quadrat of the grid.

All the survey points falling on the territory under investigation are classified as reported in Table 3:

- artificial surfaces;
- agricultural surfaces;
- forest and semi-natural areas: forests and other lands;
- wetlands;
- waterbodies.

The points falling on formations identified as TOF are respectively classified as woodlots or tree rows and constitute the first phase sample. The main attributes as the surface of each woodlot and tree row and the length of the tree rows are measured at video. Subsequently, in the field, the woodlots and the tree rows are classified according to their silvicultural system (coppice, high forest), dendrologically labelled and dendrometrically estimated (total callipering, hypsometrical and incremental measuring).

To estimate scattered trees a sub-sample of the survey points, stratified according to the classes (i-v) was randomly selected and constitutes the second phase sample. The sub-sample can be sized approximately proportional to the number of survey points of the first phase sample falling in each class. The number of scattered trees (trees not included in forests, woodlots and tree rows) is counted at video inside a circle with a preordained radius centred on each point of the second phase sample. Subsequently, a further sub-sample among the survey points of the second phase sample is randomly extracted approximately proportional to the number of survey points of second phase falling in each class (i-v). The latter sub-sample is the third phase sample. Each scattered tree falling in a circle with a preordained radius centred on each point of the third phase sample is counted, dendrologically classified, callipered, hypsometrically and incrementally measured.

6.4.2 Operative protocol

The developed sampling scheme and the survey methodology can be described in consecutive steps listed in the following protocol.

1a – On each landscape units several survey points are dislocated according to a tessellated stratified sampling, on a grid with quadrats of 1 km x 1 km overlaid on digital aerial orthophotos (nominal scale 1:10.000).

1b – All the survey points falling on the each landscape unit are photo-interpreted and classified as: artificial surfaces; agricultural surfaces; forest and semi-natural areas: forests and other lands; wetlands; waterbodies.

2a – All the woodlots, according to INFC classification, which contain at least one survey point are considered as the sample of woodlots.

2b – The size (area) of each woodlot afferent to the points of the step 2a is measured on screen.

2c – Each woodlot of the step 2a is visited and every single tree of the woodlot is dendrologically classified and callipered with a minimum DBH threshold of 7.5 cm; the height of a proper number of trees is measured to obtain the hypsometric equation of the stand; furthermore each woodlot is classified according to the silvicultural system (coppice, high forest).

3a – All the tree rows, according to INFC classification, which contains at least one survey point are considered as the sample of tree rows.

3b – The size (area and length) of each tree row afferent to the points of the step 3a is measured at video.

3c – Each tree row of the step 3a is visited and every single tree of the tree row is dendrologically classified and callipered with a minimum DBH threshold of 7.5 cm; the height of a proper number of trees is measured to obtain the hypsometric equation of the row; furthermore each tree row is classified according to the silvicultural system (coppice, high forest).

4a – A sub-sample of the survey points of the step 1b is randomly selected and is considered as the second phase sample.

4b – The number of each scattered tree (trees not included in forests, woodlots and tree rows) falling inside a circle with a radius of 100 metres centred on the points of the step 4a is counted on screen trough photo-interpretation of digital ortho-photos.

4c – A sub-sample of the survey points of the step 4a is randomly selected and is considered as the third phase sample.

4d – Each point of the step 4c is visited and the species, the diameter at breast height (DBH) above a minimum threshold of 7.5 cm and the height of every single scattered tree falling inside the circle with a radius of 100 metres centred on the points of the step 4c is recorded.

6.4.3 Application of the protocol to the case study

The sampling scheme and the survey methodology developed have been tried and tested in five landscape units localized in different Italian regions. Diverse morphological and altitudinal contexts characterise the five landscape units: open plain (area north of the river Piave, Pordenone – Friuli), carbonate hills (Verona – Veneto), valley bottom plain

(Lucca – Tuscany), terrigenous relief with peaks and rock pins (Ariano Irpino, Campania), terrigenous hills (Troina and Nicosia – Sicily).

The test areas in each landscape unit have been plotted by means of a grid with quadrats of side 1 km and have a definite size as reported in Table 10. The sample is represented by the survey points randomly selected one in each quadrat of the grid. Each survey point has been classified in the classes (i-v) as described in the paragraph 6.4.1, on digital aerial ortophotos with a nominal scale 1:10.000. Each point falling on TOF has been considered and the main attributes as the surface of woodlots and tree rows and the length of the tree rows have been measured at video.

TABLE 10: CHARACTERIZATION OF TOF SAMPLING IN THE TEST AREAS

ID	Landscape units	Surface (km^2)	Number of survey points (first phase sample)	Number of survey points (second phase sample) *	Number of survey points (third phase sample) *
1	Friuli – open plains	936	936	47	18
2	Veneto – carbonate hills	330	330	16	9
3	Tuscany – valley bottom plains	297	297	15	12
4	Campania – terrigenous relief with peaks and rock pins	1.345	1.345	67	24
5	Sicily – terrigenous hills	625	625	31	15

* The second and third phase samples have been used only for the assessment of scattered trees outside forests.

Subsequently, a sub-sample of points, of size about equal to 5% and approximately proportional to the number of survey points of the first phase sample falling in each class (i-v), was randomly selected, with a minimum of two points in each class, where it was possible (second phase sample): 47 survey points on area 1; 16 survey points on area 2; 15 survey points on area 3; 67 survey points on area 4; 31 survey points on area 5.

In correspondence of each point of the sub-sample a circle with a radius of 100 metres has been centred and the number of scattered trees falling inside the circle was counted. The woodlots and the forest tree rows identified in the first phase have been visited and classified according to the prevail silvicultural system. Into each woodlot and tree row, every single tree has been dendrologically identified and callipered above a minimum threshold of diameter of 7.5 cm and the height of a proper number of trees has been measured to obtain the hypsometric equation of the stand.

To estimate the scattered trees, a sub-sample of the survey points of the second phase sample, of size about equal to 33% and approximately proportional to the number of survey points of the second phase sample falling in each class (i-v) was randomly selected, with a minimum of two points in each class, where it was possible (third phase sample): 18 survey points on area 1; 9 survey points on area 2; 12 survey points on area 3; 24 survey points on area 4; 15 survey points on area 5. For each one of the survey points of the third phase sample, the species, the DBH and the height of each scattered tree falling inside a circle with a radius of 100 metres and centred on the point have been noticed.

To estimate the wood biomass of each identified tree outside forest, the two-way volume equations of the Italian national forest inventory (INFI, 1984) have been adopted.

The content of carbon stocked in the biomass of each measured tree outside forest was obtained from the tree volume data through the application of the biomass expansion factors, the basal density and the root/shoot ratio presented by APAT (2007) and shown in Table 11 and assuming that the fraction of carbon in dry mass is of 0,5 (IPCC, 1997).

TABLE 11: BIOMASS EXPANSION FACTORS, BASAL DENSITY AND ROOT/SHOOT RATIO (APAT, 2007).

Forest type		BEF	Basal density ($Mg\ m^{-3}$)	Root/Shoot ratio
High forest	Spruce forests	1,29	0,38	0,29
	Fir forest	1,34	0,38	0,28
	Mountain pine	1,33	0,47	0,36
	Mediterranean pine	1,53	0,53	0,33
	Other conifer forests	1,37	0,43	0,29
	Beech forests	1,36	0,61	0,20
	Turkey oak forests	1,45	0,69	0,24
	Other oak forests	1,42	0,67	0,20
	Other broadleaves	1,47	0,53	0,24
Coppice	Beech forests	1,36	0,61	0,20
	Chestnut forests	1,33	0,49	0,28
	Hornbeam forests	1,28	0,66	0,26
	Other deciduous oak forests	1,39	0,65	0,20
	Turkey oak forests	1,23	0,69	0,24
	Evergreen oak forests	1,45	0,72	1,00
	Other broadleaves	1,53	0,53	0,24
	Coppice with conifer	1,38	0,43	0,29

6.4.4 Results and discussion

In the investigated test areas, woodlots and tree rows totally represent about 2% of the territorial surface. The number of tree rows clearly prevails on the number of woodlots. However, main differences in size between the two categories of TOF are found in landscape units located on plains (see Table 12 and Table 13).

In all test-areas, TOF are found principally on land with agricultural land-use, in high number and small dimensions of woodlots and tree rows, contributing to the fragmentation of the landscape mosaic.

The number of woodlots gradually decreases from hills to lowlands, where scattered trees (Table 14) and tree rows are more widespread. In open plains, the number of tree rows is much higher than in other landscape units, in terms of number, surface, total length and mean length per hectare.

TABLE 12: MAIN RESULTS OF THE PROPOSED SAMPLING METHODOLOGY APPLIED TO WOODLOTS IN THE CASE STUDY.

ID test areas	Number ($N\ km^{-2}$)	Surface ($ha\ km^{-2}$)	Wooden biomass volume ($m^3\ km^{-2}$)	Carbon content in living biomass ($Mg\ km^{-2}$)
1	1,8	0,43	74,9	34,2
2	2,7	0,61	14,0	6,5
3	0	0	0	0
4	5,1	0,74	51,0	25,7
5	2,8	0,32	12,1	6,3

TABLE 13: MAIN RESULTS OF THE PROPOSED SAMPLING METHODOLOGY APPLIED TO TREE ROWS IN THE CASE STUDY.

ID test areas	Number ($N\ km^{-2}$)	Length ($m\ km^{-2}$)	Wooden biomass volume ($m^3\ km^{-2}$)	Carbon content in living biomass ($Mg\ km^{-2}$)
1	37,8	3821	278,2	126,4
2	6,4	945	109,0	49,3
3	4,5	679	169,0	81,8
4	18,3	1573	145,9	71,5
5	10,7	227	6,7	3,0

TABLE 14: MAIN RESULTS OF THE PROPOSED SAMPLING METHODOLOGY APPLIED TO SCATTERED TREES IN THE CASE STUDY.

ID test areas	Number ($N\ km^{-2}$)	Wooden biomass volume ($m^3\ km^{-2}$)	Carbon content in living biomass ($Mg\ km^{-2}$)
1	78,2	28,7	12,2
2	199,6	29,6	13,0
3	378,5	201,9	94,8
4	135,8	66,6	34,2
5	76,2	28,2	13,4

One of the most immediate results of a TOF inventory is the assessment of the surface covered by these formations. The presence of woodlots is more relevant in the landscape unit characterized by terrigenous relief with peaks and rock pins (Campania). The tree rows are of major importance in open plains of Friuli.

Another important result of the TOF inventory is represented by the total wooden biomass and consecutively by the related carbon content.

The total carbon content stored in the wooden biomass of TOF, related to the investigated surface of test-areas, is on average 121 Mg/km^2. The main amount of carbon is stored in TOF of lowland landscape units, with value of more than 170 Mg/km^2. However, these results must be considered as tentative values which are also probably underestimated: the wood biomass of each tree outside forests has been estimated through the two-way volume equations of the first Italian national forest inventory (INFI, 1984), suitable for trees which have grown inside forests. It is worth nothing that trees grown in small woodlots or tree rows or as scattered ones have probably higher volume than trees grown inside forests, although having the same DBH and height. For this reason, using the two-way volume equations of the first Italian national forest inventory to TOF probably entail an underestimation of the biomass assessment.

The proposed sampling and survey protocol is based on the integration of remotely sensed data elaboration and field surveys of relatively expeditious application. The methodological operations, both of photo-interpretation and in the field, are easier respect to the conventional forest inventories: the detection on digital orthophotos of TOF formations is relatively easy and fast and the access in TOF lands is generally direct and easier that to forest land, as TOF are generally found on farms and urban environments, and the dendrometric survey less difficult. The accuracy of estimates (standard errors around 20% - 30%) is relatively satisfactory, if compared to the effort of sampling.

The developed protocol adopts a sampling scheme matching with the structure of already existing inventories, facilitating the application and the integration in existing large-scale inventories (i.e. the first phase of Italian NFI). This is of relevant importance in the perspective of the advisable hypothesis to extent the proposed protocol for inventory of TOF at national scale, exploiting the first phase points of the Italian NFI.

Both the interpretation of remotely-sensed imagery and the fieldwork prove to be easier than in a classical forest inventory, as TOF recognition in the VHR imagery is obviously clearer, access in the field is more direct and measurement is simpler In the case of a region of 100 km^2 and under sampling intensity and conditions similar to those of the case studies, an expert photo-interpreter requires half a day to perform first- and second-phase steps using orthophotos while a team of two forest technicians requires roughly another one day to record the attributes in the field on the sampled TOF

The adopted methodology provides an initial assessment of the TOF formations as carbon sinks in Italy. Extrapolating the estimates from the test-areas and relating them to the whole national surface, it is possible to tentatively infer that the carbon stored in the wooden biomass of TOF can be considered not less than 30 million tonnes at national level.

Moreover, in the present investigation incremental data were not systematically collected, but on the basis of a review of few scattered data and of data existing in literature, it is possible to tentatively infer that the annual carbon fixation in aboveground wooden biomass of TOF in Italy is not less than 1 million tonnes per year.

6.5 Perspectives

The estimates in the test-areas show a not negligible quantity in terms of wooden biomass and carbon content of carbon stored by the TOF, even considering that the further carbon content in soil and litter is not included. Moreover, the carbon stored in TOF is intended to increase in coming years, mainly in relation to their further territorial expansion resulting from the recent Common Agricultural Policy orientations.

The qualitative and quantitative assessment of TOF and the estimate of their landscape and ecological value are the basis for the right planning and management choices aimed to the conservation of this resource and to the improvement of the ecosystem services they provide. This consideration is of relevant importance especially in the perspective of eligibility of the agro-forestry sector to contribute to the national count of greenhouse gas emissions in the second commitment period of the Kyoto Protocol.

Despite the numerous financings of political orientations involving directly many rural or urban realities characterized by the presence of TOF (e.g. Rural Development Policy 2007-2013), no reliable data on the number, distribution and ecological characterization of these formations are available at the moment on large-scale.

The main expected perspective is the adoption of the developed protocol to investigate TOF formations at national-scale.

7. Sector sampling for assessing small woodlots

The previous Chapter 6 showed a valid application at large-scale of the developed methodology for TOF inventory. However, according to the proposed methodology, all trees of each sampled woodlot should be callipered. An additional procedure has been developed in order to survey woodlots in a more expeditious way, by sampling trees within the woodlots.

Usually, fixed- or variable-area plots are adopted to select trees within a study region (see e.g. Gregoire and Valentine, 2008, Chapter 7 and 8). However, small patches such as woodlots are difficult to be sampled unbiasedly by plots because of the edge effect: trees near to the edge of woodlots have less chance of being included in the sample than inner trees. While edge effects are negligible and can be ignored when the inclusion zones of trees are much smaller than the study region, when sampling small woodlots the inclusion zones are of the same order of magnitude than the study region: in these situations a relevant amount of negative bias can be induced by ignoring edge effect. Edge problems have been well investigated in literature and several solutions have been proposed (e.g. Gregoire and Valentine, 2008, section 7.5). Unfortunately, any solution is likely to elongate the field work with respect to the simple plot procedures.

In this framework a sampling method referring to as sector sampling has been recently proposed by Iles and Smith (2006) and proves to be particularly useful for sampling small cluster of trees within irregularly shaped regions such as small woodlots.

In this chapter an *ad hoc* sampling protocol is proposed in order to survey woodlots in expeditious way through the random and independent selection of circular sections inside woodlots. A pivot point is purposively selected within the woodlot, usually in the middle of woodlot (see Figure 9); then a sector of fixed angle θ centred on a direction randomly selected on $0-2\pi$ is emanated from the pivot point and all the trees within the sector are selected. As consequence, all trees in the woodlot have the same probability $\theta/2\pi$ of being included in the sample.

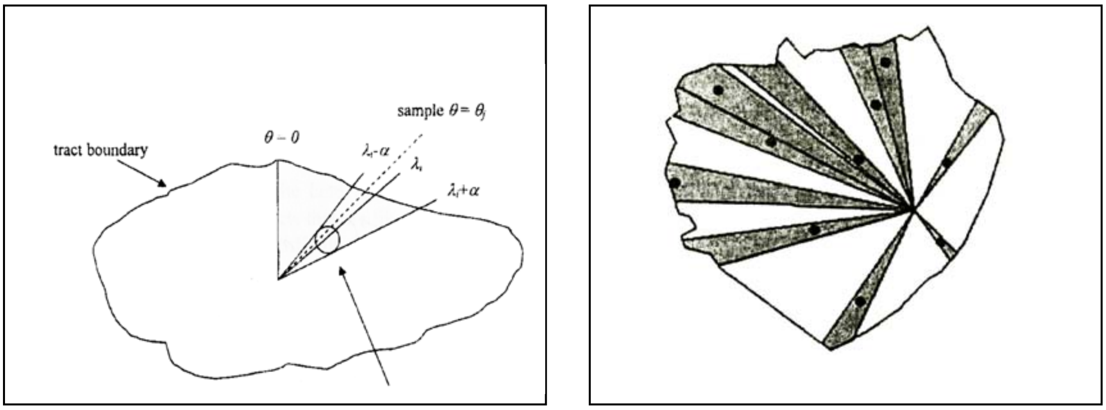


FIGURE 9: SECTOR SAMPLING FOR SMALL WOODLOTS

7.1 Two-stage sector sampling

To estimate the forest attributes of a population of woodlots a two-stage sector sampling is proposed. The two-stage sampling scheme involves a first stage in which a sample of woodlots are selected by means of a fixed-size sampling scheme and a second stage in which R pseudo-replication of sector sampling are performed in the woodlots selected in the first stage and the interest variable is recorded for all the trees lying within the selected sectors.

The statistical properties of the two-stage sampling strategy here proposed are considered in the following paragraphs.

7.1.1 Proposed sampling scheme and estimators

Let W be a population of N small woodlots on a delineated study area. Denote by a_j the size of unit j and by T_j the total amount of an interest variable Y (e.g. timber volume) in the j-th woodlot. Finally, suppose that the population total

$$T = \sum_{j \in W} T_j$$

is the interest quantities to be estimated.

In order to estimate T, let S be a sample of $n \leq N$ woodlots selected in the first stage in accordance with a probabilistic scheme and denote by π_j and π_{jh} ($h > j \in W$) the first- and second-order inclusion probabilities induced by the scheme. If the selected woodlots were completely surveyed and the T_j s were recorded for each $j \in \mathsf{S}$, then the Horvitz-Thompson (HT) estimator

$$\hat{T}_1 = \sum_{j \in \mathsf{S}} \frac{T_j}{\pi_j} \qquad (16)$$

provided an unbiased estimator for T with variance

$$\mathrm{V}_1\left(\hat{T}_1\right) = \sum_{j \in \mathsf{U}} \sum_{h > j} \left(\pi_j \pi_h - \pi_{jh}\right) \left(\frac{T_j}{\pi_j} - \frac{T_h}{\pi_h}\right)^2 \qquad (17)$$

where henceforth E_1 and V_1 will denote expectation and variance with respect to the first sampling stage. Moreover, the well known Sen-Yates-Grundy variance estimator

$$V_1^2 = \sum_{j \in \mathsf{S}} \sum_{h > j} \frac{\pi_j \pi_h - \pi_{jh}}{\pi_{jh}} \left(\frac{T_j}{\pi_j} - \frac{T_h}{\pi_h}\right)^2 \qquad (18)$$

constituted an unbiased estimator of (17), in the sense that $\mathrm{E}_1(V_1^2) = \mathrm{V}_1(\hat{T}_1)$.

Unfortunately, owing to the costs and time involved, in real situations a complete survey cannot be performed within each woodlot selected in the first stage. Accordingly, the first-phase survey is only hypothetical and its treatment has had the sole aim of constructing the theoretical basis for the analysis of the subsequent stage.

Denote by U_j the population of trees lying within the j-th woodlot and let y_l be the value of the interest variable Y corresponding to the l-th tree in U_j, in such a way that T_j can be written as the population total

$$T_j = \sum_{l \in \mathsf{U}_j} y_l$$

In real situations, sample surveys are performed within the selected woodlots in order to estimate the T_j s. Actually a second stage of sampling is performed in which for any $j \in \mathsf{S}$ a sample of trees, say Q_j, is selected from U_j in accordance with a suitable scheme and the interest variable is recorded for any $l \in \mathsf{Q}_j$.

If the sector sampling is adopted in the second stage, the HT estimator of T_j based on a single sector turns out to be

$$\hat{T}_j = \frac{2\pi}{\theta} \sum_{l \in Q_j} y_l \qquad (19)$$

Without any edge effect, (19) is unbiased for T_j with variance

$$\sigma_j^2 = \frac{2\pi}{\theta} \sum_{l \in U_j} y_l^2 + \frac{2\pi}{\theta^2} \sum_{h > l \in U_j} y_l y_h \theta_{lh} - T_j^2 .$$

where θ_{lh} is the overlap of the angles of width θ constructed around the directions joining the l-th and h-th trees to the pivot point (Lynch, 2006).

As customary in forest survey, the sampling scheme is replicated R_j times, in the sense that R_j sectors are randomly and independently emanated from the pivot point giving rise to R_j estimates of type (4), say $\hat{T}_{1,j},\ldots,\hat{T}_{R_j,j}$, which constitute R_j iid realizations of a random variable with expectation T_j and variance σ_j^2. Accordingly, on the basis of very standard results on iid observations, the arithmetic mean of the R_j estimates

$$\hat{\hat{T}}_j = \frac{1}{R_j} \sum_{i=1}^{R_j} \hat{T}_{i,j} \qquad (20)$$

constitutes an unbiased and consistent ($R_j \to \infty$) estimator of T_j with variance σ_j^2 / R_j. Moreover, the empirical variance of the R estimates

$$s_j^2 = \frac{1}{R_j - 1} \sum_{i=1}^{R_j} (\hat{T}_{i,j} - \hat{\hat{T}}_j)^2$$

constitutes an unbiased and consistent estimator of σ_j^2.

Gregoire and Valentine (2008, chapter 10) provide an excellent introductory chapter on the issue of sampling discrete objects scattered over a region. The authors emphasize that most of these schemes may be conveniently re-formulated in terms of Monte-Carlo integration, also giving a list of references from the early 90s in which such intuition was first developed. In this setting, the interest parameter T_j can be expressed as an integral over $(0-2\pi)$ and (20) may be viewed as a Monte Carlo integration, thus focusing on the problem of how to effectively select the R_j directions onto $(0-2\pi)$. Despite its theoretical simplicity, the completely random selection of directions, referred to as uniform random sampling (URS), may lead to uneven coverage of the study area. Hence, the random systematic sampling (RSS) based on a partition of $(0-2\pi)$ into R_j sectors of equal width and the random selection of a direction within each sector should ensure a better coverage of the study area. The scheme has a long standing in statistical literature (see e.g. Overton and Stehman, 1993) and is proven to be unbiased and invariably more efficient than URS, in the sense that $\mathrm{E}_{RSS}(\hat{\hat{T}}_j) = T_j$ and $\mathrm{V}_{RSS}(\hat{\hat{T}}_j) \leq \sigma_j^2 / R_j$ where E_{RSS} and V_{RSS} obviously denote expectation and variance with respect to the random systematic selection of directions onto $(0-2\pi)$. This is a well known result which had been reached, mutatis mutandi, in Monte Carlo integration (see e.g. Haber, 1966). Moreover, as to the estimation of $\mathrm{V}_{RSS}(\hat{\hat{T}}_{Rj})$, it can proven that s_j^2 / R_j constitutes a conservative estimator of $\mathrm{V}_{RSS}(\hat{\hat{T}}_j)$, in the sense that $\mathrm{E}_{RSS}(s_j^2/R_j) \geq \mathrm{V}_{RSS}(\hat{\hat{T}}_j)$ (e.g. Wolter, 1985, Theorem 2.4.1).

Then, if the RSS estimates $\hat{\hat{T}}_j$ are used in (16) instead of the actual values T_j, the two stage estimator of T turns out to be

$$\hat{T}_2 = \sum_{j \in \mathrm{S}} \frac{\hat{\hat{T}}_j}{\pi_j} \qquad (21)$$

Obviously (21) no longer constitutes an HT estimator and it is referred to as a two-stage analogue of the HT estimator. Hedayat and Sinha (1991, Corollary 7.5) proves that (21) is unbiased with variance

$$\mathrm{V}\left(\hat{T}_2\right) = \mathrm{V}_1(\hat{T}_1) + \sum_{j \in \mathrm{W}} \frac{V_{RSS}(\hat{\hat{T}}_j)}{\pi_j} \qquad (22)$$

where henceforth E and V will denote expectation and variance with respect to both the sampling stages. Note that the second term is (22), represent the increases in variance due to the estimation of totals within selected woodlots. If $\pi_{jh} > 0$ for each $h > j = 1,2,\ldots,N$ and if s_j^2 / R_j provided an unbiased estimator of $V_{RSS}(\hat{\hat{T}}_{Rj})$ then

$$V^2 = \sum_{j \in \mathrm{S}} \sum_{h > j} \frac{\pi_j \pi_h - \pi_{jh}}{\pi_{jh}} \left(\frac{\hat{\hat{T}}_j}{\pi_j} - \frac{\hat{\hat{T}}_h}{\pi_h} \right)^2 + \sum_{j \in \mathrm{S}} \frac{s_j^2}{R_j \pi_j} \qquad (23)$$

would be an unbiased estimator of (22) (Hedayat and Sinha, 1991, Corollary 7.5). However, since s_j^2 / R_j provides a conservative estimator of $V_{RSS}(\hat{\bar{T}}_j)$, then V^2 obviously constitutes a conservative estimator (22), i.e. $\mathrm{E}\left(V^2\right) \geq \mathrm{V}\left(\hat{T}_2\right)$.

7.1.2 Simulation study

7.1.2.1 Dataset

The performance of the estimators proposed in the previous section was checked by means of a simulation study performed on two artificial populations of small woodlots. The density and the size of the woodlots as well as the timber volumes of trees within woodlots roughly resembled the results of some assessments performed on the case study presented in the paragraph 7.2.

A set of $N = 100$ woodlots was considered. The size a_j (ha) and the density d_j (number of trees per ha) of each woodlot were generated from a bivariate log-normal distribution with expectations 0.25 ha and 625 trees per ha, coefficients of variations 0.48 and 0.68 and correlation coefficient 0.15. The number of trees in each woodlot, say M_j, was then achieved as the integer nearest to $a_j d_j$ and, for each of the M_j trees the timber volume (m^3) was generated from a log-normal distribution with expectation 0.15 m^3 and standard deviation 0.3 m^3 , in such a way that the total volume T_j was achieved as the sum of the M_j volumes within the woodlot. Finally the T_j s were rescaled in such a way to give a total volume $T = 2300$ m^3 (coefficient of variation 1.15) while the timber volumes of trees within each woodlot were rescaled accordingly. Figure 10 plots the woodlots sizes against their total volumes.

From these data, two population were constructed in accordance with the presumed shapes: a population of circular-shaped woodlots (referred to as CIRCLES population) and a population of rectangular-shaped woodlots (referred to as RECTANGLES populations) with basis three times longer than height. Finally, the M_j trees were randomly and independently selected within each circular or rectangular woodlot.

7.1.2.2 Sampling simulation

For each woodlot population (CIRCLES and RECTANGLES) and each sample size $n = 25,50,100$, ten thousand samples of woodlots were selected in the first stage by means of simple random sampling without replacement (SRSWOR) and Sunter sampling. Obviously the case of $n = 100$ coincides with the selection of the whole population, i.e the absence of the first stage of sampling.

As to the use of Sunter sampling, it is at once apparent from (17) that the variance of the HT estimator becomes as small as the π_j s are approximately proportional to the T_j s. Consequently, since the T_j s should be nearly proportional to their sizes a_j s, the first-order inclusion probabilities should be suitably chosen to be proportional to woodlot sizes. Brewer and Hanif (1983) list 43 fixed-size sampling schemes giving rise to first-order inclusion probabilities proportional to the size of an auxiliary variable, the so called ΠPS designs. All these schemes give rise to first-order inclusion probabilities of type $\pi_j = na_j / A$, where $A = a_1 + \cdots + a_N$, providing that $na_j < A$, while differing in the second-order inclusion probabilities. Among these schemes, Sunter sampling (Sunter, 1977) constitutes a nearly ΠPS design which provides remarkable simplification over strictly ΠPS designs with no important drawback in efficiency lost (Särndal et al., 1992, p.93). Moreover, as pointed out by Sunter (1977), Sunter sampling gives rise to invariably positive second-order inclusion probabilities which also guarantees nonnegative values for the Sen-Yates-Grundy variance estimator of type (18), which in turn guarantees non-negative values for the estimator of type (23).

As to the second stage, the use of R sectors were presumed within each selected woodlot, where $R = 8$ when $n = 25$, $R = 4$ when $n = 50$ and $R = 2$ when $n = 100$ in such a way to give a whole sampling effort of 200 sectors. Then, for each simulated first-stage sample S and each selected woodlot $j \in \mathsf{S}$, the pivot point was set on the centre of circular- or rectangular shaped woodlot, the whole angle $(0 - 2\pi)$ was partitioned into R sectors of equal width, a direction was randomly selected within each sector and a sector of width $\theta = \pi / 5$ (36°) centred onto the direction was emanated from the pivot point. Finally all the trees lying within each selected sector was sampled. For each simulated sample S, the T_j s were estimated by means of equation (20), while the total volume T was estimated by the two-stage estimator (21) and its sampling variance was estimated by means of equation (23). In turn, the estimate of the sampling variance gave rise to an estimate of the relative standard error (RSE), say $R\hat{S}E = V / \hat{T}_2$.

7.1.2.3 Performance indicators

The knowledge of the first- and second-order inclusion probabilities allowed for the straightforward computation of the first-stage variance $\mathrm{V}_1(\hat{T}_1)$. On the other hand, the variance of the second-stage estimator $\mathrm{V}(\hat{T}_2)$ as well as the expectation of the RSE estimator $\mathrm{E}(R\hat{S}E)$ are empirically evaluated for each population, each first phase sampling scheme and each sample size on the basis of the Monte Carlo distributions of $\hat{T}_2$ and $R\hat{S}E$, respectively. While the expectation of the RSE estimator (ERSEE) can be used to determine the conservative nature of V^2, the variance of $\hat{T}_2$ allows for the computation of the relative root mean squared error (RRMSE) $\sqrt{\mathrm{V}(\hat{T}_2)}/T$ and the fraction of variance of $\hat{T}_2$ due to the first stage of sampling (FVFSS), $\mathrm{V}_1(\hat{T}_1)/\mathrm{V}(\hat{T}_2)$.

7.1.2.4 Results

Table 15 and Table 16 report the percent values of RRMSE, FVFSS and ERSEE for each artificial population, each first-stage sampling scheme and each sample size.

Comparison of Table 15 vs Table 16 shows that woodlot shapes heavily impacts on the efficiency of the sampling strategy. More precisely if woodlot shapes are nearly symmetric around pivot points (as in the case of circles around their centres) the R sectors are approximately of the same sizes with a subsequent low variability of the R estimates. On the other hand, if woodlot shapes are asymmetric around pivot points (as in the case of rectangles around their centres), the R sector may have very different sizes with a subsequent high variability of the R estimates. Obviously, shape effect decreases as the number of sector increases. As to the choice of first-stage scheme, the use of a ΠPS designs with inclusion probabilities proportional to woodlot sizes provides, as expected, remarkable improvements over the use of equal-probability sampling with an efficiency (variance ratio) of Sunter sampling with respect to SRSWOR of about 1.5 in all the situations. Finally, for circular-shaped woodlot, when few sectors suffice to provide accurate estimates of woodlot totals, most variability is due to the first stage of sampling; in this case few sector should be used to survey a large sample (or the whole population) of woodlots. The best effort allocation is not so clearly stated in the RECTANGLES population, when the use of two sectors for surveying the whole woodlot population has the same efficiency of the use of four sectors for surveying half of the woodlot population suitably selected by means of Sunter samplping. Finally, V^2 proved to be an adequate estimator of the two-stage variance giving moderate overestimation in all situations.

In order to take into account a clumped distribution of trees within woodlots, the simulation study was repeated by spreading trees in small clusters of 3 elements with cluster centres randomly distributed over the woodlots. This further study leaded to results very similar to those contained in Table 15and

Table 16 which have here been omitted.

TABLE 15: PERFORMANCE OF THE TWO-STAGE ANALOGUE OF THE H-T ESTIMATOR AND OF THE ESTIMATOR OF THE SAMPLING VARIANCE FOR AN ARTIFICIAL POPULATION OF 100 CIRCULAR-SHAPED WOODLOTS.

n	R	RRMSE	FVFSS	ERSEE
100	2	3.65%	0.00%	3.92%
SRSWOR				
50	4	12.02%	92.31%	12.09%
25	8	20.11%	98.23%	20.19%
SUNTER				
50	4	7.50%	82.84%	7.62%
25	8	13.62%	96.80%	13.97%

TABLE 16: PERFORMANCE OF THE TWO-STAGE ANALOGUE OF THE H-T ESTIMATOR AND OF THE ESTIMATOR OF THE SAMPLING VARIANCE FOR AN ARTIFICIAL POPULATION OF 100 RECTANGULAR-SHAPED WOODLOTS

n	R	RRMSE	FVFSS	ERSEE
100	2	9.68%	0.00%	9.78%
SRSWOR				
50	4	14.95%	59.39%	15.05%
25	8	20.78%	93.08%	21.15%
SUNTER				
50	4	10.26%	43.91%	10.32%
25	8	14.05%	90.17%	14.88%

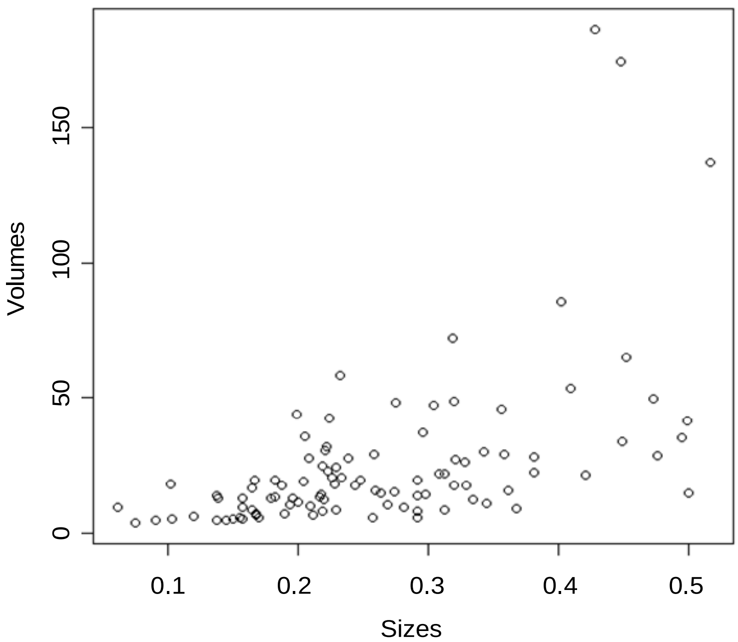


FIGURE 10: WOODLOT SIZES PLOTTED AGAINS TOTAL VOLUMES OF THE TWO ARTIFICIAL POPULATIONS OF 100 WOODLOTS ADOPTED IN THE SIMULATION STUDY.

7.2 Case study

The feasibility of the proposed methodology has been tested in a study area corresponding to the administrative district of Viterbo (Central Italy). The study area has a total surface of 406 km^2 in which all the woodlots have been investigated through photo-interpretation and field survey.

The methodology has revealed itself of satisfactory and of valuable practical application, especially if compared to the quite limited sampling effort. The methodology of sampling and survey, the operative protocol and the results coming from the application in the area of the case study are discussed in the following paragraphs.

7.2.1 Methodology of sampling and survey

The study area has been identified on remote sensed orthorectified images at high geometrical resolution. On the basis of this support, a census of the whole population of woodlots laying in the boundary of the administrative district of Viterbo (406 km^2) has been conducted.

A grid with quadrat of 1 km side has been placed on the study area for a better visual investigation of the total surface. Each woodlot found on the study area has been detected in the first stage and the main attributes as the surface and the perimeter of each woodlot have been measured at video. In the second stage, in the field, the woodlots have been classified according to their silvicultural system (coppice, high forest) and dendrologically and dendrometrically characterized through total callipering and hypsometrical measurement. Successively, the woodlots have been surveyed according to the proposed sector sampling methodology. For each woodlot $R = 2$ sector samplings of width 36° have been randomly selected in the range $(0 – \pi)$ and $(\pi – 2\pi)$. A sub-sample of woodlots was randomly selected and in each sub-sampled woodlot $R = 4$ sector samplings of width 36° have been randomly selected, one for each quadrant range $(0 – \pi/2)$, $(\pi/2 – \pi)$, $(\pi – 3/2\pi)$, $(3/2\pi – 2\pi)$. A further sub-sample of woodlots was randomly selected in which $R = 8$ sector samplings of width 36° have been randomly selected in the range$(0 – \pi/4)$, $(\pi/4 – \pi/2)$, $(\pi/2 – 3/4\pi)$, $(3/4\pi – \pi)$, $(\pi – 5/4\pi)$, $(5/4\pi – 3/2\pi)$, $(3/2\pi – 7/4\pi)$, $(7/4\pi – 2\pi)$.

7.2.2 Operative protocol

The operative protocol of sector sampling methodology is described in consecutive steps listed as follow.

1a – Photo interpretation on digital ortophotos (nominal scale 1:10.000) of the landscape unit.

1b – Each woodlot laying on the investigated surface is identified.

1c – The size (area) of each woodlot of the step 1b is measured on screen.

2a – For each woodlot of the step 1b, two bisecting lines are randomly generated, one for each portion of the circumference, respect to the north direction, between (0°-180°) and (180°-360°).

2b – A sub-sample of woodlots of the step 1b (in the rate of approximately 50%) is randomly selected and two further bisecting lines are randomly generated, for a total of 4 bisecting lines one for each quadrant of the circumference of width (0°-90), (90-180°), (180°-270°), (270°-360°), respect to the north direction.

2c – A sub-sample of woodlots of the step 2b (in the rate of approximately 50%) is randomly selected and four further bisecting lines are randomly generated, starting from an approximately central pivot point, for a total of 8 bisecting lines one for each portion of the circumference of width (0°-45°), (45°-90°), (90°-135°), (135°-180°), (180°-225°), (225°-270°), (270°-315°),(315°-360°), respect to the north direction.

3a – Each woodlot of the step 1b is visited and each tree is dendrologically classified and callipered with a minimum DBH threshold of 7.5 cm; the height of a proper number of trees is measured to obtain the hypsometric equation of the stand; furthermore each woodlot is classified according to the silvicultural system (coppice, high forest).

3b – In each woodlot of the step 1b, an approximately central pivot point is localized in the field. The bisecting lines according with the steps 2a, 2b and 2c are identified in radial direction starting from the pivot point.

3c – A sector of width 36° centered on each bisecting line is generated.

3d – Each tree of each sector sample is dendrologically classified and callipered with a minimum DBH threshold of 7.5 cm; the height of a proper number of trees is measured to obtain the hypsometric equation.

7.2.3 Application of the protocol to the case study

39 woodlots resulted located in the municipality of Viterbo. The volume of each woodlots was recorded by full callipering and two-way volume equation of the Italian national forest inventory (INFI, 1984). Three sample sizes of woodlots were considered for the sector sampling: more precisely $n = 39, 21, 11$ woodlots were selected by means of SRSWOR. The woodlots were respectively partitioned into two, four and eigth portions. Subsequently one sector was randomly thrown within each portion starting from the woodlots center and volumes of the trees lying in the sector were assessed. The HT estimator based on single sectors was calculated accordingly with (19) and the arithmetic mean of the volumes estimated in the R sectors was calculated for each woodlot accordingly with (20).

7.2.4 Results

In the investigated test area delimitated by the boundary of the city of Viterbo, 39 woodlots have been found with an average surface of 2360 m^2. The volume of each woodlot was observed in the field and the total amount of volume resulted of 933 m^3, with an average value of volume for each woodlot of 24 m^3.

Each sector was surveyed in the field and the volume for sector sampling has been calculated accordingly with the HT estimators (19) and (20) giving values quite similar to those measured for the whole woodlots: the total amount of volume resulted by sector sampling is of 913 m^3, with an average value of volume for each woodlot of 23 m^3 (see Table 17).

TABLE 17: MAIN RESULTS OF THE PROPOSED SECTOR SAMPLING METHODOLOGY APPLIED TO THE WOODLOTS OF THE CASE STUDY.

ID	Total surface (m^2)	Volume (m^3) (mean of HT estimators per sectors)			Total measured volume (m^3)	ID	Total surface (m^2)	Volume (m^3) (mean of HT estimators per sectors)			Total measured volume (m^3)
		R = 2	R = 4	R = 8				R = 2	R = 4	R = 8	
1	2288	28			24	**21**	4931	32			30
2	3726	40			55	**22**	1084	18			17
3	1392		7		13	**23**	2042	46			25
4	3842	78			29	**24**	1841		27		24
5	3526		30		25	**25**	1796			19	20
6	1152			23	20	**26**	826			10	19
7	1131		14		9	**27**	1731			30	33
8	1580			20	18	**28**	1308	8			7
9	2183		9		8	**29**	2161			23	22
10	2589	23			11	**30**	1728		21		40
11	1072	6			3	**31**	1122	7			10
12	1227		15		19	**32**	3374			33	29
13	3672			42	35	**33**	2397		26		19
14	3720			37	33	**34**	2817	27			24
15	1497	46			24	**35**	4854	12			18
16	4923		14		59	**36**	1869	43			44
17	883	2			4	**37**	1538	41			32
18	2131	20			37	**38**	4229		4		58
19	2994			5	5	**39**	3365	14			14
20	1498			13	18	**Mean**	2360	27	17	23	24

The proposed sector sampling methodology has revealed itself of satisfactory and of valuable practical application. The values of volume coming from the sector sampling survey find good correspondence with those measured for the whole surface of the woodlots in a quite great number of cases.

7.2.5 Discussion

The comparison of the complete survey of the whole woodlot with the more expeditious sampling survey performed on a restricted portion of the woodlot in circular sectors, showed noticeably advantages provided by sector sampling.

Notably, small patches such as woodlots are difficult to be sampled unbiasedly by plots because of the edge effect, trees near to the edge of woodlots have less chance of being included in the sample than inner trees. The proposed sector sampling methodology provides a suitable solution to shorten the time usually needed to survey woodlots, while maintaining the quality of the survey. The proposed sector sampling methodology, in fact, considers the variable due to the edge effects: all trees in the woodlot have the same probability ($\theta/2\pi$) of being included in the sector sample and certainly trees from the inner part and trees from the edge of the woodlot will be encompassed in the same sector sample.

The main expected perspective is the application of the sector sampling methodology to survey TOF formations as woodlots, especially in case of the adoption of the developed methodology protocol to investigate TOF formations at national-scale. The Sector sampling methodology will guarantee a more expeditious way to survey woodlots while maintaining high standard of quality results.

Moreover, the developed protocol for sector sampling survey is suitable and should be adopted also for the survey of woodlots on a small scale, where all the woodlots identified on VHR images on a small surface must be visited in the fields. In this case the sector sampling methodology allows a considerable reduction in time and effort of the survey while providing suitable volume data.

As a very general guideline for performing two stage sector sampling it should be suggested an adequate choice of pivot points in such a way to render the sector size variability as small as possible joined with the use of few sectors (usually two) within a large first-stage sample of woodlot suitably selected by a designs with inclusion probabilities proportional to woodlot sizes.

8. Final considerations

The multiple functions and the great variety of goods and services provided by TOF are widely recognized and represent an important resource that must be quantitatively well-known and protected.

This thesis provides a solution to the widespread and increasing need for more detailed information on the quantitative and qualitative assessment of TOF resources and on their distribution.

The application of the proposed methodologies allows the knowledge of the quantitative and qualitative attributes of TOF which are of fundamental importance in the view of:

1) a more comprehensive forest and land planning and management considering the whole territory as a mosaic composed of various patches among which the trees in the agro-forestry system plays an important role with their contribution in terms of ecological corridors, goods and services, wooden biomass and related sink of carbon;
2) a major protection and conservation of TOF resources and a better assessment of their potential as carbon sink, especially in the concrete perspective raised by most of countries to elect the Land Use Land Use Change and Forestry (LULUCF) activities of the agro-forestry sector from 2012 in the second commitment period of the Kyoto Protocol.

The innovations provided by this research compared to other methodological proposals are reported below.

1) The development of an *ad hoc* methodology for TOF inventory proved to be easily applicable exploiting the first-phase of the conventional multi-phase forest inventories and merging into the already existing network of large-scale forest inventories. Few similar studies have been conducted taking in account these fundamental characteristics (see e.g. Lister et al. 2009), however none reports results about the statistical properties of the proposed strategies. The statistical estimators proposed in the methodology developed in this thesis prove to be robust and of useful application, especially after the simulation study in which they were tested.

2) The *ad hoc* developed methodology for TOF inventory implies a feasible practical application verified in the case study, a significant reduction in the time needed for the survey and a satisfactory accuracy of the estimates with a relative reduction of the effort sampling.

3) Moreover, also the sector sampling methodology proves to provide a valid solution for sampling small surfaces as woodlots, solving the practical problem related to edge effect considerably reducing the time for the survey, while providing reliable and satisfactory results from collected data.

4) The developed protocols thanks to their potentiality to be implemented in the first-phase of the conventional large-scale forest inventories allow a collection of information on TOF at lower cost of implementation than other independent methodologies for TOF inventory.

This thesis underlines the importance of TOF resources and demonstrates that the quantitative and qualitative assessment of TOF resources can be feasible conducted through the implementation of the proposed methodologies. The main auspicable perspective of this research is the adoption of the developed protocols on large areas, to collect all the data and information on agroforestry patches indispensable for a more comprehensive land planning and management.

9. References

Agrimi M., portoghesi L., 2002. Rimboschimenti e alberature frangivento nella lotta alla desertificazione: considerazioni sulla realtà italiana. L'Italia Forestale e Montana, 4: 309-318.

Alexandre D. Y., Lescure J. P., Bied-Charreton M. and Fotsing J. M., 1999. Contribution à l'état des connaissances sur les arbres hors forêt (TOF) IRD-FAO, Orléans, France, 185 pp.

APAT, 2007 – Italian Greenhouse Inventory 1990-2005. National Inventory Report 2007. Annual Report for submission under the UN Framework Convention on Climate Change and the European Union's Greenhouse Gas Monitoring Mechanism, settore LULUCF.

Asamoah-Boateng B., 2003. Distribution and biodiversity of Tree Resources Outside Forest (TROF) in Southern Ghana. Paper of International Institute for Geo-Information Science and Earth Observation, March 2003.

Auclair, D., Prinsley, R., and Davis, S., 2000. Trees on farms in industrialised countries: silvicultural, environmental and economics issues. Proceedings of XXI IUFRO World Congress 7-12 August 2000, Kuala Lumpur, Malaysia, p. 776.

Baddeley A.J., Jensen E.B.V., 2004. Stereology for statisticians. Chapman and Hall, London.

Bagnoud, N., Schmithüsen, F. and Sorg, J-P., 1995. Les parcs à karité et néré au sud Mali - Analyse du bilan économique des arbres associés aux cultures. Bois et Forêts des Tropiques244: 9-23.

Barabesi L., 2003. A Monte Carlo integration approach to Horvitz-Thompson estimation in replicated environmental designs. Metron 61:355-374.

Barabesi L., Marcheselli M., 2003. A modified Monte Carlo integration. Internat Math J 3:555-565.

Barabesi L., Marcheselli M., 2008. Improved strategies for coverage estimation by using replicated line-intercept sampling. Environ Ecol Stat 15:215-139

Barbati A.,Corona P., Chiriacò M. V., Portoghesi L., 2009. Indici di produttività boschiva, rilievo indici di relazione tra produzioni forestali e biomassa residuale associata, analisi del mercato della biomassa forestale in Italia. ENEA Report RSE/2009/51.

Beer, J., Ibrahim, M. and Schlövoigt, A., 2000. Timber production in tropical agroforestry systems of Central America. Forest and society - the role of research. Proceedings of XXI IUFRO World Congress 7-12 August 2000, Kuala Lumpur, 777-786.

Bellefontaine R., Petit S., Pain-orcet M., Deleporte P., Bertault J.G., 2002. Trees outside forests - Towards better awareness. FAO Conservation Guide n.35, Rome.

Ben Salem, B., 1991. Combattre et prévenir l'érosion éolienne dans les régions arides. Unasylva 2 , 164: 33-39.

Bergeret A. and Ribot J., 1990. L'arbre nourricier en pays sahélien Editions de la Maison des Sciences de l'Homme, Paris, 237 pp.

Bertrand A., 1993. La sécurisation foncière: condition de la gestion viable des ressources naturelles renouvelables. CIRAD. Nogent sur Marne and Dakar, Sénégal. 30 pp.

Biasioli M., 2002. Alberi fuori foresta - dialogo internazionale e due casi di studio: Francia e Inghilterra. Dendronatura 2: 23-30.

Boffa J.-M., 2000a. Les parcs agroforestiers en Afrique de l'Ouest: clés de la conservation et d'une gestion durable. Unasylva51, 200: 11-17.

Boffa J.-M., 2000b. Les parcs agroforestiers en Afrique subsaharienne FAO Conservation Guide 34, FAO, Rome, 258 pp.

Borin M., Maccatrozzo G., 2005. Immobilizzazione della CO_2 da parte delle siepi campestri. Alberi e Territorio 7/8: 47-52.

Brewer K.R.W., Hanif M., 1983. Sampling with Unequal Probabilities. Springer, New York.

Brown S., 1997. Les forêts et le changement climatique: les terres boisées comme puits de carbone. In Comptes rendus du X I Congrès forestier mondial. 13-22 octobre 1997 Antalya, Turkey. Volume 1, theme 4, 105 -114. Antalya.

Clement C.R., 1989. The potential use of the pejibaye palm in agroforestry systems. Agroforestry Systems7, 3: 201-212.

Cochran, W.G., 1977. Sampling Techniques, Wiley, New York.

Cordy C.B. and Thompson C.M., 1995. An application of deterministic variogram to design-based variance estimation. Mathematical Geology **27**: 173-205.

Corona P., 2000 – Introduzione al rilevamento campionario delle risorse forestali. Edizioni CUSL, Firenze.

Corona P., Chiriacò M.V., Salvati R., Marchetti M., Lasserre B., Ferrari B., 2009. Proposta metodologica per l'inventario su vasta scala degli alberi fuori foresta. L'Italia Forestale e Montana 6: 367-380.

Corona P., Fattorini L., 2006 – The assessment of tree row attributes by stratified two-stage sampling. European Journal of Forest Research, 125: 57-66.

Cullotta S., La Mantia T., Barbera G., 1999. Descrizione e ruolo dei sistemi agroforestali in Sicilia. In: AA.VV., «Secondo Congresso Nazionale di Selvicoltura per il miglioramento e la conservazione dei boschi italiani», vol. IV., p: 429-438.

De Natale F., Gasparini P., Puzzolo V., Tosi V., 2003. Stima del grado di copertura forestale da ortofoto e applicazione della definizione di bosco negli inventari forestali. L'Italia Forestale e Montana, 4: 289-300.

De Vries P.G., 1986. Sampling Theory for Forest Inventories. Springer-Verlag, Berlin.

Deffar G.,1998. Non-wood forest products in Ethiopia. Data collection and analysis for sustainable forest management in ACP countries. FAO-EC Partnership Programme. Addis Ababa. Document internet: www.fao.org/forestry.

Endreny T.A., 2002. Forest buffer strips. Mapping the water quality benefits. Journal of Forestry 1: 35-40.

EPA, 2002. Guidance for choosing a sampling design for environmental data collection. EPA QA/G-5S. US Environmental Protection Agency, Washington, D.C.

FAO, 1986. Brise-vent et rideaux abris avec référence particulière aux zones sèches FAO Conservation Guide 15, Rome, 385 pp.

FAO, 1989. Forestry and nutrition: a reference manual. Rome.

FAO, 1993. Forestry policies in the Near East region: analysis and synthesisVol.111, Rome.

FAO, 2001. Forest Resources Assessment 2000- Main Report of the Forest Resources Assessment Programme, Forestry Department. Rome.

FAO, 2010. Global Forest Resources Assessment 2010- Main Report. Rome.

Fattorini L., Marcheselli M. and Pisani C., 2006. A three-phase sampling strategy for large-scale multiresources forest inventories. Journal of Agricoltural, Biological and Environmental Statistics 11: 296-216.

Gordon A.M., Newman S.M. and Williams P.A., 1997. Temperate agroforestry: an overview. In: Gordon A.M. and Newman S.M. (eds) Temperate Agroforestry Systems, pp 1–8. CAB International, Wallingford, UK

Gregoire T.G., Valentine H.T., 2008. Sampling Strategies for Natural Resources and the Evironment. Chapman & Hall, New York, USA.

Haber S., 1966. A modified Monte-Carlo quadrature. Math Comput 20:361-368.

Hedayat, A.S., Sinha, B.K., 1991. Design and Inference in Finite Population Sampling.Wiley, New York.

Holmgren P., Masakha E.J. et Sjöholm H., 1994. Not all african land is being degraded : a recent survey of trees on farms in Kenya reveals rapidly increasing forest resources. Ambio 3, 7: 390-395.

IFNI, 1984 – Tavole di cubatura a doppia entrata. Ministero dell'Agricoltura e delle Foreste, Istituto Sperimentale per l'Assestamento Forestale e per l'Alpicoltura, Trento.

Iles K., Smith N.J., 2006. A new type of sample plot that is particularly useful for sampling small cluster of objects. Forest Science, 52, 148-154.

INEA, 1999. Annuario dell'agricoltura italiana 1998: Volume LII. Il Mulino, Bologna.

INFC, 2003. Manuale di fotointerpretazione per la classificazione delle unità di campionamento di prima fase. Inventario Nazionale delle Foreste e dei Serbatoi Forestali di Carbonio. MiPAF - Direzione Generale per le Risorse Forestali Montane e Idriche, Corpo Forestale dello Stato. Documento a cura dell'Istituto Sperimentale per l'Assestamento Forestale e per l'Alpicoltura, Trento.

IPCC, 1997 – Revised 1996 IPCC Guidelines for National greenhouse Gas Emisssion Inventories. Three Volumes: Reference Manual, Reporting Guidelines and Workbook. IPCC/OECD/IEA. IPCC WG1 Technical Support Unit, Hadley Centre, Metereological Office, Bracknell, UK.

Johansson S., Storage conditions of yeheb (*Cordeauxia edulis Hemsl.*) seeds. Graduation thesis SLU 2006.

Kleinn C., 1999. Compilation of information on Trees outside forests:Regional Special Study for Latin América, including also Haiti. Contribution to Forest Resources Assessment 2000, FAO. Tropical Agicultural Research and Training Centre (CATIE). 87 pp.

Kleinn C., 2000. On large area inventory and assessment of trees outside forests. Unasylva 51:3-10.

Kleinn C., 2002. New technologies and methodologies for national forest inventories. Unasylva 53:10-15.

Kleinn K., Morales D., 2002. Assessment of Tree Resources Outside the Forest. European Tropical Forest Research Network (ETFRN) News 36.

Kleinn K., Morales D., Ramirez C., 2001. Large area inventory of Tree Resources Outside the forest: what is the problem? Paper presented at Proceedings of a IUFRO 4.11 Conference "Forest Biometry, Modeling and Information Science", University of Greenwich, 26-29 June 2001.

Kuchelmeister G., 2000. Des arbres pour le millénaire urbain: le point sur la foresterie urbaine. Unasylva 1: 49-55.

Kumar, A. and Sastry, C.B. 999. Le réseau international de recherche sur le bambou et le rotin. Unasylva 0, 198: 48-53.

Leakey R.R.B., 1996. Definition of agroforestry revisited. Agroforestry Today 8(1): 5–7

Leipzig Declaration on Conservation and Sustainable Utilization of Plant Genetic Resources for Food and Agriculture. International technical conference on plant genetic resources. Leipzig, Germany, 17-23 june 1996.

Lister A., Scott C. and Rasmussen S., 2009. Inventory of trees in nonforest areas in the Great Plains States. USDA Forest Service Proceedings, RMRS-P-56.17.

Lopez A., Schlönvoigt A., Ibrahim M., Kleinn C., Kanninen M., 1999. Cuantificación del carbono almacenado en el suelo de un sistema silvopastoril en la zona atlántica de Costa Rica. Agroforestería En Las Américas, 23 (6): 51-53.

Lynch T.B., 2006. Variance reduction for sector sampling, Forest Science, 52, 3, 251-261.

Marinelli M., 2010. Agroforestry systems in mediterranean areas prone to desertification. L'italia forestale e montana 65 (3): 271-280.

Martel F., Whyte W.F., 1992. Quoted from: www.rainforestinfo.org.au/

Massa B., La Mantia T., 1997. Benefits of hedgerows-windbreaks for birds and their valorisation in sustainable agriculture. Agricoltura Mediterranea, 127: 332-341.

Mezzalira G., 1997a. Siepi per la produzione di legna da ardere nella pianura veneta. Sherwood 21: 13-18.

Mezzalira G., 1997b. Valore apistico delle siepi campestri. Sherwood 22: 11-14.

Moyo S., 1999. *Trees outside forests (TOF). Zimbabwe country report* Projet GCP/INT/679/EC. EC-FAO partnership programme (1998-2000). Forest Conservation, Education and Research Service. FAO, Rome. 35 pp.

Nair P.K.R., 1987. Agroforestry Systems Inventory. Agrofor Syst 5: 301–317

Opsomer J.D., Breidt F.J., Moisen G.G., Kauermann G., 2007. Model-assisted estimation of forest resources with generalized additive models. J Am Stat Assoc 102:400-409.

Overton W.S., Stehman S.V., 1993. Properties of designs for sampling continuous spatial resources from a triangular grid. Coomun Statist - Theory Meth 22:2641-2660.

Paletto A., De Natale F., Gasparini P., Morelli S., Tosi V., 2006. L'Inventario degli Alberi Fuori Foresta (IAFF) come strumento di analisi del paesaggio e supporto alle scelte di pianificazione territoriale. Forest@ 3 (2): 253-266. [online] URL: http://www.sisef.it/

Pettenella D., Serafin S., 1999. La convenienza economica nell'impiego di biomasse a fini energetici in impianti su piccola scala: I filari a ceduo di platano. Sherwood 50: 23-28.

Rathore C.S., Prasad R., 2002. TOF resource study and management: assessment methodologies and institutional approaches in India. Proceedings of the Expert Consultation on Enhancing the Contribution of Trees Outside Forests To Sustainable Livelihoods held at FAO Rome – 26-28 November 2001 (Sadio S, Kleinn C, Michaelsen Teds.). FAO 2002: pp. 133-147.

Saket M., Branthomme A. and Piazza M., 2010. FAO NFMA. Support to developing countries on national forest monitoring and assessment. In: National forest inventories, pathways for common reporting. In: Tomppo, E., Gschwantner, T., Lawrence, M., McRoberts, R.E. (eds.), Springer, Heidelberg, Germany, pp. 585-596.

Särndal C. E., Swensson B. & Wretman, J., 1992. Model assisted survey sampling. Springer, New York.

Schofield N.J., 1993. Tree planting for dryland salinity control in Australia. In: Prinsley RT (ed) The Role of Trees in Sustainable Agriculture, pp 1–24. Kluwer Academic Publishers,The Netherlands

Schroeder P., 1994. Carbon storage benefits of agroforestry systems. Agroforestry Systems, 27: 89-97.

Secretariat of the Convention on Biological Diversity, April 2000. Sustaining life on Earth. How the Convention on Biological Diversity promotes nature and human well-being ISBN 92-807-1904-1.

Sharma R., 1993. The socioeconomic evaluation of social forestry policy in India. Ambio22, 4: 219-224.

Sinclair F.L., 1991. University education in agroforestry. Proceedings (8) of the 10th World Forestry Congress, Paris, September 1991. Revue Forestiere Francaise Hors Serie No. 8, pp 79–86

Sinclair F.L., 1999. A general classification of agroforestry practice. Agroforestry Systems 46: 161–180,

Somarriba, E 1990. Sustainable timber production from uneven-aged shade stands of Cordia alliodora in small coffee farms. Agroforestry Systems 10: 253-263

Stevens, D.L. 1997. Variable density grid-based sampling designs for continuous spatial populations. Environmetrics 8: 167-195.

Sunter, A.B., 1977. List sequential sampling with equal or unequal probabilities without replacement. Journal of the Royal Statistical Society. Series C (Applied Statistics), 26, 3, 261-268.

Tabacchi G., De Natale F., Floris A., Gagliano C., Gasparini P.,Scrinzi G. and Tosi V., 2005. Italian National Forest Inventory: Methods, State of the Project, and Future Developments. Proceedings of the Seventh Annual Forest Inventory and Analysis Symposium.

Taylor D.A., 1999. Les conditions de prospérité des entreprises rurales basées sur les produits forestiers non ligneux. Unasylva 0, 198: 3-8.

Thomson J.T., 1994. Schéma d'analyse des incitations institutionnelles dans le domaine de la foresterie communautaire FAO, Rome,140 pp.

Tokola T., 2006. Asia. In: Kangas A, Maltamo M (eds) Forest inventory. Methodology and applications. Springer, Dordrecht, pp 309–324.

Tosi V., Monteccone V., 2004. Standard per gli inventari forestali di area vasta. Uno studio comparativo per il territorio italiano. Forest@ 1 (2): 148-164. [online] URL: http://www.sisef.it/

Unasylva, 1999. La FAO et la foresterie. Unasylva 198 50) : 63. Les produits non ligneux et la création de revenus.

Unruh J.D., Houghton R.A. and Lefebvre P.A., 1993. Carbon storage in agroforestry: an estimate for sub-Saharan Africa. Climate Research3 : 39-52.

Whittier J., Rue D. and Haase S., 1995. Urban tree residues: results of the first national inventory. Journal of Arboriculture 1, 2: 57-62.

Williams P.A., Gordon A.M., Garrett H.E. and Buck L., 1997. Agroforestry in North America and its role in farming systems. In: Gordon AM and Newman SM (eds) Temperate Agroforestry Systems, pp 9–84. CAB International, Wallingford, UK

Wolter K.M., 1985. Introduction to variance estimation. Springer-Verlag, New York, USA.

Wong J., 2001. Policy, inventory and management of trees outside forests in a densely populated country: a case study of the UK. Expert Consultation on Trees Outside Forests "Enhancing the contribution of trees outside forests to sustainable livelihoods", FAO/HQ 26-28 November 2001, Rome.

Web references

http://www.fao.org/forestry/tof/en/

http://www.rainforestinfo.org.au

http://www.infc.it

http://www.communityforest.org.uk

Appendices

Appendix 1. Definitions

Total area

Total area (of country), including area under inland water bodies, but excluding offshore territorial waters.

Total land area is defined as total area excluding inland waters.

Tree

A woody perennial with a single main stem, or in the case of coppice with several stems, having a more or less definite crown.

Includes: bamboos, palms and other plants meeting the above criterion.

Shrubs and bushes

Woody perennial plants, generally of more than 0,5 m and less than 5 m and without a definite crown.

Forest

Land with tree crown cover (or equivalent stocking level) of more than 10 percent and area of more than 0.5 hectares (ha). The trees should be able to reach a minimum height of 5 m at maturity in situ. May consist of either closed forest formations where trees of various storeys and undergrowth cover a high proportion of the ground, or open forest formations with a continuous vegetation cover, in which tree crown cover exceeds 10 percent. Young natural stands and all plantations established for forestry purposes which have yet to reach a crown density of 10 percent or tree height of 5 m are included under forest, as are areas normally forming part of the forest area which are temporarily unstocked as a result of human intervention or natural causes but which are expected to revert to forest.

Includes: forest nurseries and seed orchards that constitute an integral part of the forest; forest roads, cleared tracts, firebreaks and other small open areas; forest in national parks, nature reserves and other protected areas such as those of specific scientific, historical, cultural or spiritual interest; windbreaks and shelterbelts of trees with an area of more than 0.5 ha and width of more than 20 m; plantations primarily used for forestry purposes, including rubberwood plantations and cork oak stands.

Excludes: land predominantly used under agricultural or urban land use.

The term specifically excludes stands of trees established primarily for agricultural production, for example fruit tree plantations. It also excludes trees planted in agroforestry systems.

Other wooded land

Land with either a crown cover (or equivalent stocking level) of 5 to 10 percent of trees, able to reach a height of 5 m at maturity in situ; or a crown cover (or equivalent stocking level) of more than 10 percent of trees not able to reach a height of 5 m at maturity in situ (e.g. dwarf or stunted trees); or with shrub or bush cover of more than 10 percent.

Other official FAO definitions useful to label a portion of land are reported below.

Other land

Land not classified as forest or other wooded land as defined above.

Includes: agricultural land, meadows and pastures, built-on and urban areas, barren land, etc.

Inland water

Area occupied by major rivers, lakes and reservoirs.

Appendix 2. Uniform random sampling vs. tessellation stratified sampling

Suppose at first that the study area $\mathcal{A}$ can be exactly tessellated by n non overlapping polygons, i.e suppose $\mathcal{A} = \mathcal{R} = \bigcup_{i=1}^{n} Q_i$. Then, suppose a point, say **u**, is randomly thrown onto $\mathcal{R}$ and the unit j is selected if $\mathbf{u} \in a_j$. Accordingly, the inclusion probability of the j unit is given by $\tau_j = |a_j| / |\mathcal{R}|$ and the HT estimator of T based on a single sample point **u** turns out to be

$$\hat{T}(\mathbf{u}) = \sum_{j=1}^{N} \frac{y_j}{\tau_j} z_j(\mathbf{u}) \qquad \text{(A.1)}$$

where $z_j(\mathbf{u})$ is a Bernoulli variable equal to 1 if $\mathbf{u} \in a_j$ and 0 otherwise. For the subsequent developments, it is worth noting that the population total T can be expressed as

$$T = \frac{1}{|\mathcal{R}|} \int_{\mathcal{R}} \hat{T}(\mathbf{u}) d\mathbf{u} \qquad \text{(A.2)}$$

Obviously, a study area cannot be adequately sampled by means of only one point. Rather, in accordance with the protocol of the uniform random sampling, n points $\mathbf{u}_1, \ldots, \mathbf{u}_n$ are randomly and independently selected on $\mathcal{R}$. Thus, denote by $\hat{T}_i$ the estimate of type (A.1) obtained at the sample point $\mathbf{u}_i$ and by

$$\overline{T}_n = \frac{1}{n} \sum_{i=1}^{n} \hat{T}_i \qquad \text{(A.3)}$$

the arithmetic mean of the n estimates, usually referred to as the HH estimator. Since the $\mathbf{u}_i$ s are n independent realizations of the random variable **u** uniformly distributed over $\mathcal{R}$, the HT estimates $\hat{T}_1, \ldots, \hat{T}_n$ may be viewed as transforms of the $\mathbf{u}_i$ s. Accordingly, owing to (A.2),

$$\mathrm{E}_{URS}(\overline{T}_n) = \frac{1}{n} \sum_{i=1}^{n} \mathrm{E}_{URS} \left\{ \hat{T}(\mathbf{u}_i) \right\} = \frac{1}{n} n \int_{\mathcal{R}} \hat{T}(\mathbf{u}) \frac{1}{|\mathcal{R}|} d\mathbf{u} = T$$

and

$$\mathrm{V}_{URS}(\overline{T}_n) = \frac{1}{n^2}\sum_{i=1}^{n}\mathrm{V}_{URS}\left\{\hat{T}(\mathbf{u}_i)\right\} = \frac{1}{n^2}n\left[\int_{\mathcal{R}}\hat{T}^2(\mathbf{u})\frac{1}{|\mathcal{R}|}d\mathbf{u} - \left\{\int_{\mathcal{R}}\hat{T}(\mathbf{u})\frac{1}{|\mathcal{R}|}d\mathbf{u}\right\}^2\right] = \frac{1}{n}(S - T^2)$$

where E_{URS} and V_{URS} denote expectation and variance with respect to the uniform random placement of points over $\mathcal{R}$ and

$$S = \frac{1}{|\mathcal{R}|}\int_{\mathcal{R}}\hat{T}^2(\mathbf{u})d\mathbf{u}$$

On the other hand, if in accordance with the protocol of the tessellation stratified sampling, a point is randomly selected within each polygon , then $\mathbf{u}_1,\ldots,\mathbf{u}_n$ are independent random variables each of which uniformly distributed in the corresponding quadrat. Accordingly,

$$\mathrm{E}_{TSS}(\overline{T}_n) = \frac{1}{n}\sum_{i=1}^{n}\mathrm{E}_{TSS}\left\{\hat{T}(\mathbf{u}_i)\right\} = \frac{1}{n}\sum_{i=1}^{n}\int_{\mathrm{Q}_i}\hat{T}(\mathbf{u})\frac{n}{|\mathcal{R}|}d\mathbf{u} = \sum_{i=1}^{n}T_i = T$$

and

$$\mathrm{V}_{TSS}(\overline{T}_n) = \frac{1}{n^2}\sum_{i=1}^{n}\mathrm{V}_{TSS}\left\{\hat{T}(\mathbf{u}_i)\right\} = \frac{1}{n^2}\sum_{i=1}^{n}\left[\int_{\mathrm{Q}_i}\hat{T}^2(\mathbf{u})\frac{n}{|\mathcal{R}|}d\mathbf{u} - \left\{\int_{\mathrm{Q}_i}\hat{T}(\mathbf{u})\frac{n}{|\mathcal{R}|}d\mathbf{u}\right\}^2\right] = \frac{1}{n}\sum_{i=1}^{n}S_i - \sum_{i=1}^{n}T_i^2$$

where E_{TSS} and V_{TSS} denote expectation and variance with respect to the tessellation stratified placements of points over $\mathcal{R}$, while

$$T_i = \frac{1}{|\mathcal{R}|}\int_{\mathrm{Q}_i}\hat{T}(\mathbf{u})d\mathbf{u}$$

and

$$S_i = \frac{1}{|\mathcal{R}|}\int_{\mathrm{Q}_i}\hat{T}^2(\mathbf{u})d\mathbf{u}$$

Thus, keeping in mind that the sum of the T_i s gives T and the sum of the S_i s gives S , it follows that

$$\mathrm{V}_{URS}(\overline{T}_n) - \mathrm{V}_{TSS}(\overline{T}_n) = \sum_{i=1}^{n}T_i^2 - \frac{1}{n}T^2 = \sum_{i=1}^{n}(T_i - \overline{T})^2$$

where $\bar{T} = T / n$. From the above relation it is apparent that the efficiency gain of tessellation stratified sampling with respect to uniform random sampling invariably equals n times the variance of the T_i s.

On the other hand, if the study area is irregularly shaped and cannot be exactly tessellated by polygons, the covering region $\mathcal{R}$ turns out to be greater than $\mathcal{A}$. In this case the uniform random scheme and the tessellation stratified scheme are not directly comparable. Indeed, under the uniform random scheme, points are selected over $\mathcal{A}$ while, under the tessellation stratified scheme, points are selected over the enlarged region $\mathcal{R}$. Thus, in some (peculiar) situations the uniform random scheme may outperform the tessellation stratified scheme.

Appendix 3. Hansen-Hurvitz and Horvitz-Thompson estimation

From (A.1) and (A.3), the HH estimator $\overline{T}_n$ can be rewritten as

$$\overline{T}_n = \frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{N}\frac{y_j}{\tau_j}z_j(\mathbf{u}_i) = \frac{1}{n}\sum_{j=1}^{N}\frac{y_j}{\tau_j}\sum_{i=1}^{n}z_j(\mathbf{u}_i) = \frac{1}{n}\sum_{j=1}^{N}\frac{y_j}{\tau_j}n_j \qquad \text{(A.4)}$$

where

$$n_j = \sum_{i=1}^{n} z_j(\mathbf{u}_i)$$

represents the number of times unit j has been selected by the n points. Since $n_j = 0$ for each $j \notin \mathsf{S}$, (A.4) is equivalent to

$$\overline{T}_n = \frac{1}{n}\sum_{j\in\mathsf{S}}\frac{y_j}{\tau_j}n_j \qquad \text{(A.5)}$$

As is well known from the theory of finite population sampling, S constitutes the minimal sufficient statistic (e.g. Basu 1969). Accordingly, it is apparent from (A.5) that $\overline{T}_n$ is not a function of the minimal sufficient statistic, as it also depends on the number of times the units are selected. Thus, by using the Rao-Blackwell method, the expectation of $\overline{T}_n$ conditional to S provides an estimator which is as good or better than $\overline{T}_n$.

In order to perform the Rao-Blackwell method, some preliminary considerations are necessary. Denote by Q_j the set of labels identifying the quadrats occupied by a_j. Accordingly

$$a_j = \bigcup_{i\in\mathsf{Q}_j} a_{ji}$$

and

$$|a_j| = \sum_{i\in\mathsf{Q}_j}|a_{ji}|$$

where a_{ji} denotes the portion of a_j included in the quadrat Q_i and $|a_{ji}|$ denotes its size. Under tessellation stratified sampling a point is randomly selected within each quadrat. Hence, from straightforward consideration, the probability that unit j enters S, usually referred to as first-order inclusion probability, turns out to be

$$\pi_j = \Pr(n_j > 0) = 1 - \Pr(n_j = 0) = 1 - \prod_{i \in \mathsf{Q}_j} \left(1 - n\frac{|a_{ji}|}{|\mathcal{R}|}\right) \tag{A.6}$$

Then, from the Rao-Blackwell method and from (A.4) it follows that

$$\mathrm{E}_{USS}\{\overline{T}_n \mid \mathsf{S}\} = \mathrm{E}_{TSS}\left\{\frac{1}{n}\sum_{j=1}^{N}\frac{y_j}{\tau_j}\sum_{i=1}^{n} z_j(\mathbf{u}_i) \mid \mathsf{S}\right\} = \frac{|\mathcal{R}|}{n}\sum_{j=1}^{N}\frac{y_j}{|a_j|}\sum_{i=1}^{n}\mathrm{E}_{TSS}\{z_j(\mathbf{u}_i) \mid \mathsf{S}\}$$

Obviously $z_j(\mathbf{u}_i) = 0$ when $j \notin \mathsf{S}$ and/or when $i \notin \mathsf{Q}_j$, in such a way that $\mathrm{E}_{TSS}\{z_j(\mathbf{u}_i) \mid \mathsf{S}\} = 0$ for each $j \notin \mathsf{S}$ and each $i \notin \mathsf{Q}_j$. On the other hand, for each $j \in \mathsf{S}$ and $i \in \mathsf{Q}_j$

$$\mathrm{E}_{TSS}\{z_j(\mathbf{u}_i) \mid j \in \mathsf{S}\} = \Pr\{z_j(\mathbf{u}_i) = 1 \mid j \in \mathsf{S}\} = \frac{\Pr(\mathbf{u}_i \in a_{ji} \mid j \in \mathsf{S})}{\Pr(j \in \mathsf{S})} = \frac{n\,|a_{ji}|}{|\mathcal{R}|\pi_j}$$

Accordingly, the Rao-Blackwell method gives rise to

$$\mathrm{E}_{TSS}\{\overline{T}_n \mid \mathsf{S}\} = \frac{|\mathcal{R}|}{n}\sum_{j \in \mathsf{S}}\frac{y_j}{|a_j|}\sum_{i \in \mathsf{Q}_j}\frac{n\,|a_{ji}|}{|\mathcal{R}|\pi_j} = \sum_{j \in \mathsf{S}}\frac{y_j}{\pi_j} \tag{A.7}$$

which constitutes the HT estimator of T, say $\hat{T}_{HT}$.

Obviously, when a unit lies completely within a quadrat, its first-order inclusion probability π_j trivially reduces to $n\tau_j$, while if it occupies several quadrats, the computation of (A.7) involves the painstaking quantifications of the $|a_{ji}|$s. In order to avoid such measurements a suitable approximation of (A.6) should be attempted. For a given unit j, denote by x_i the ratio $|a_{ji}|/|\mathcal{R}|$ and suppose that the unit j occupies L quadrats. Then, the inclusion probabilities (A.6) can be written as a function of type

$$\pi_j(x_1,\ldots,x_L) = 1 - \prod_{i=1}^{L}(1 - nx_i) \tag{A.8}$$

If , as usual, $|\mathcal{R}|$ is much larger than the unit sizes, then the x_i s are negligible. Thus, considering the first two terms of the Taylor series expansion of (A.8) around $x_1 = \ldots = x_L = 0$, the following approximation is generated

$$\pi_j \approx \pi_j(0,\ldots,0) + \sum_{i=1}^{L}\left[\frac{\partial \pi_j}{\partial x_i}\right]_{x_i=0} x_i = \sum_{i=1}^{L} n x_i = n\sum_{i=1}^{L}\frac{|a_{ji}|}{|\mathcal{R}|} = n\frac{|a_j|}{|\mathcal{R}|} = n\tau_j$$

Accordingly, all the population units have inclusion probabilities approximately equal to $n\tau_j$, in such a way that the HT estimator can be suitably approximated by

$$\widetilde{T}_n = \frac{1}{n}\sum_{j\in S}\frac{y_j}{\tau_j} \tag{A.9}$$

Interestingly, $\widetilde{T}_n$ also constitutes an approximation for the HH estimator (A.5). Indeed, from straightforward considerations analogous to those leading to expression (A.6), it follows that

$$\Pr(n_j > 1) = 1 - \Pr(n_j = 0) - \Pr(n_j = 1) = \pi_j - \sum_{i\in \mathrm{Q}_j} n\frac{|a_{ji}|}{|\mathcal{R}|}\prod_{l\neq i}\left(1 - n\frac{|a_{jl}|}{|\mathcal{R}|}\right)$$

In analogy with the procedure adopted for approximating the π_j s, the previous expression may be viewed as a function of L ratios $|a_{ji}|/|\mathcal{R}|$ and may be approximated by the first two terms of the Taylor series expansion around 0s. After trivial computations, the approximation gives rise to $\Pr(n_j > 1) \approx 0$. Thus, since the n_j s can be approximated by Bernoulli variables, n_j can be set equal to 1 for each $j \in \mathrm{S}$, in such a way that $\overline{T}_n$ reduces to $\widetilde{T}_n$.

Practically speaking, if the unit sizes are very small compared with the size of the whole study area, the HH and the HT estimators tend to be very similar and both of them can be conveniently approximated by $\widetilde{T}_n$.

Appendix 4. Variance estimation

In order to provide an estimator for the variance of $\tilde{T}_n$, the estimator may be viewed as an approximation to $\overline{T}_n$ or $\hat{T}_{HT}$. Since the former is obtained as the arithmetic mean of n independent, although not identically distributed, random variables $\hat{T}_1,\ldots,\hat{T}_n$,, it is more convenient to look at $\tilde{T}_n$ as an approximation of $\overline{T}_n$ and then attempt to estimate its variance by estimating the variance of $\overline{T}_n$. Indeed, it is well known that a conservative estimator for the variance of the arithmetic mean of n independent (but not identical) random variables is given by their sampling variance divided by n. Accordingly

$$\overline{V}_n^2 = \frac{1}{n(n-1)}\sum_{i=1}^{n}(\hat{T}_i - \overline{T}_n)^2$$

constitutes an approximately conservative estimator for the variance of $\overline{T}_n$, in the sense that $\mathrm{E}_{TSS}(\overline{V}_n^2) \geq \mathrm{V}_{TSS}(\overline{T}_n)$. Obviously, there will be $n - \sum_{j\in \mathrm{S}} n_j$ quadrats in which $\hat{T}_i = 0$ since no unit is selected, while for each $j \in \mathrm{S}$ there will be n_j quadrats in which $\hat{T}_i = y_j / \tau_j$. Accordingly, the previous expression can be rewritten as

$$\overline{V}_n^2 = \frac{1}{n(n-1)}\left\{\sum_{j\in \mathrm{S}}\left(\frac{y_j}{\tau_j} - \overline{T}_n\right)^2 n_j + \left(n - \sum_{j\in \mathrm{S}} n_j\right)\overline{T}_n^2\right\}$$

But keeping in mind that $\overline{T}_n$ can be approximated by $\tilde{T}_n$ and that n_j can be set equal to 1 for each $j \in \mathrm{S}$, $\overline{V}_n^2$ can be approximated by

$$\tilde{V}_n^2 = \frac{1}{n(n-1)}\left\{\sum_{j\in \mathrm{S}}\left(\frac{y_j}{\tau_j} - \tilde{T}_n\right)^2 + (n-m)\tilde{T}_n^2\right\}$$

which after some trivial computations reduces to

$$\tilde{V}_n^2 = \frac{1}{n(n-1)}\left\{\sum_{j\in \mathrm{S}}\left(\frac{y_j}{\tau_j}\right)^2 - n\tilde{T}_n^2\right\} \qquad \text{(A.10)}$$

Owing to the independence of the $\hat{T}_i$s, $\overline{T_n}$ is approximately normal, in such a way that even $\widetilde{T}_n$ is approximately normal. Accordingly, if the normal approximation holds, $\widetilde{T}_n \pm 1.96\widetilde{V}_n$ constitutes a confidence interval with coverage which tends to be greater than 95%.

Appendix 5. Estimation of a ratio

Denote by $T_{(Y)}$ and $T_{(X)}$ the population totals corresponding to the survey variables Y and X , respectively, and assume the ratio $R = T_{(Y)} / T_{(X)}$ to be the target parameter. A quite natural estimator for R is the ratio $\widetilde{R}_n = \widetilde{T}_{(Y)n} / \widetilde{T}_{(X)n}$ where $\widetilde{T}_{(Y)n}$ and $\widetilde{T}_{(X)n}$ are the estimators of type (A.9) for the corresponding population totals. Once again it is convenient to consider $\widetilde{R}_n$ as an approximation of $\overline{R}_n = \overline{T}_{(Y)n} / \overline{T}_{(X)n}$ where $\overline{T}_{(Y)n}$ and $\overline{T}_{(X)n}$ are the corresponding estimators of type (A.5). In analogy with Särndal et al (1992), using Taylor linearization $\overline{R}_n$ is approximated by

$$\overline{R}_n \approx R + \frac{\overline{T}_{(Y)n} - R\overline{T}_{(X)n}}{T_{(X)}}$$

from which

$$\mathrm{E}_{TSS}(\overline{R}_n) \approx R + \frac{\mathrm{E}_{TSS}\left\{\overline{T}_{(Y)n}\right\} - R\mathrm{E}_{TSS}\left\{\overline{T}_{(X)n}\right\}}{T_{(X)}} = R + \frac{T_{(Y)} - RT_{(X)}}{T_{(X)}} = R$$

$$\mathrm{V}_{TSS}(\overline{R}_n) \approx \frac{1}{T_{(X)}^2} \mathrm{V}_{TSS}\left\{\overline{T}_{(Y)n} - R\overline{T}_{(X)n}\right\} = \frac{1}{T_{(X)}^2} \mathrm{V}_{TSS}(\overline{D}_n)$$

where $\overline{D}_n$ is the HH estimator performed on the population values $y_j - Rx_j \ (j = 1, \ldots, N)$. Thus, in analogy with (A.10), the estimator of $\mathrm{V}_{TSS}(\overline{R}_n)$ should be

$$\widetilde{V}_{(R)n}^2 = \frac{1}{\widetilde{T}_{(X)n}^2 n(n-1)} \left\{ \sum_{j \in S} \left(\frac{y_j - Rx_j}{\tau_j} \right)^2 - n\widetilde{D}_n^2 \right\} \qquad \text{(A.11)}$$

where, in analogy with (A.9),

$$\widetilde{D}_n = \frac{1}{n} \sum_{j \in S} \frac{y_j - Rx_j}{\tau_j} \qquad \text{(A.12)}$$

However, the previous quantities cannot be computed from the sample data because they involve the knowledge of R. Accordingly, $\widetilde{R}_n$ is adopted in (A.11) and (A.12) instead of R. In this case $\widetilde{D}_n$ turns out to be 0 and (A.11) reduces to

$$\tilde{V}^2_{(R)n} = \frac{1}{\tilde{T}^2_{(X)n}\, n(n-1)} \sum_{j \in S} \left(\frac{y_j - \tilde{R}_n x_j}{\tau_j} \right)^2$$

Obviously, being based on a Taylor approximation, nothing ensures that $\tilde{V}^2_{(R)n}$ is a strictly conservative estimator of the variance of $\tilde{R}_n$. On the other hand, the approximate normality of $\tilde{R}_n$ is ensured, via the delta method, by the approximate normality $\tilde{T}_{(Y)n}$ and $\tilde{T}_{(X)n}$. Accordingly, $\tilde{R}_n \pm 1.96\tilde{V}_{(R)n}$ constitutes a confidence interval with an approximate coverage of 95%.

List of acronyms and abbreviations

AC95	Actual coverage of the 95% confidence intervals
AGGR	Aggregated spatial pattern
ATB	Above-ground tree biomass
BEF	Biomass expansion factors
DBH	Diameter at breast height
E2PSE	Expected sampling efforts performed in the second phase
E3PSE	Expected sampling efforts performed in the third phase
EPA	United States Environmental Protection Agency
ERSEE	Expectations of the RSE estimators
FAO	Food and Agricultural Organization
FVFSS	Fraction of variance due to the first stage of sampling
HH	Hansen-Hurvitz estimator
HT	Horvitz-Thompson estimator
iid	Independent and identically distributed random variables
INFC	National inventory of forests and of carbon forest sink
INFI	Italian national forest inventory
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land Use, Land Use Change and Forestry
MCPFE	Ministerial Conference on the Protection of Forests in Europe
Π **PS**	Fixed-size sampling schemes giving rise to first-order inclusion probabilities proportional to the size of an auxiliary variable
R	Ratio root/shoot
RAND	Completely random distribution
RB	Relative bias
RRMSE	Relative root mean squared error
RSE	Relative standard error
RSS	Random systematic sampling
SRSWOR	Simple random sampling without replacement
TOF	Tree outside forest
TSS	Tessellation stratified sampling
UNCED	United Nations Conference on Environment and Development
URS	Uniform random sampling
VHR	Very High Resolution