Forest inventory using field measurements

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Scope of NAFORMA Forest Inventories

- To provide information about forests for, e.g.,
  - forest and forest environment management
  - decision making in forestry and planning the use of wood and other forest products
  - national and international forestry programs and agreements
    - FAO FRA reporting
    - REDD+ MRV

Some facts and figures of Tanzania

- Country area 94.730 mill. ha
- Land area: 88.580 mill. ha, of which (FRA 2010)
  - Forest land, 33.428 mill. ha
  - Other wooded land, 11.619
- Growing stock in forest and other wooded land forest 1237 million m^3, 37 m^3/ha

The current design and method of NAFORMA

- About 34 000 plots in the entire country
- With field plot data
  - area and volume estimates for larger Districts and the groups of the Districts
- With field plot data, satellite images and digital map data
  - area and volume estimates for all Districts and Villages
  - digital wall-to-wall thematic maps

Why sampling in field data measurements

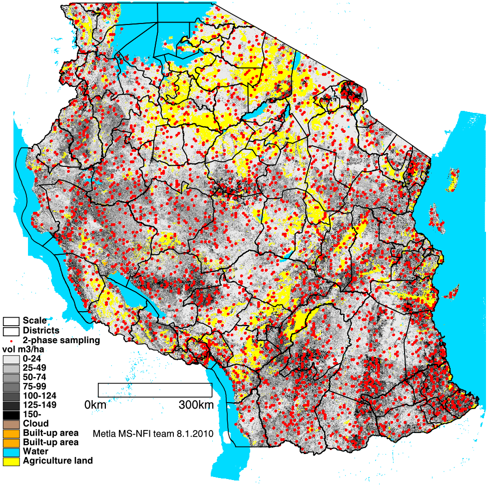
- Measuring of each unit in the population is impossible because of costs
  - In Tanzania, e.g., the number of trees, with a height of at least 1.3 m, is estimated to be over 100×10^9, the measurement of which, with 30 seconds per tree, would take for 100 crews 5000 years.
- In forests, nearby units are more similar than those further apart from each other
  - wasted resources to measure similar units

The sampling design of NAFORMA

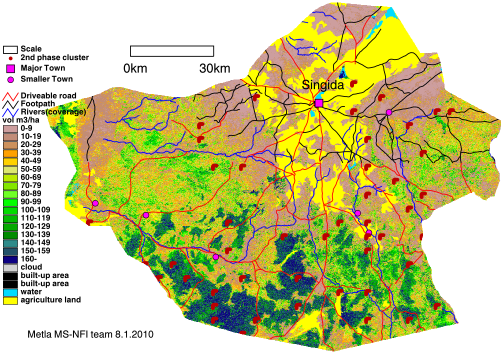
- The entire country in 2010 - early 2012, after that 5 years panel system ?
- Both temporary and permanent plots, every fourth cluster permanent to be re-measured
- NAFORMA covers all land use and land cover and ownership classes
- NAFORMA II, 2014- The entire grid in 5 years using a panel system, and starting with the permanent plots for REDD+ MRV

Clusters to be measured in 2010 - early 2012

About 3500 clusters, 33471 plots

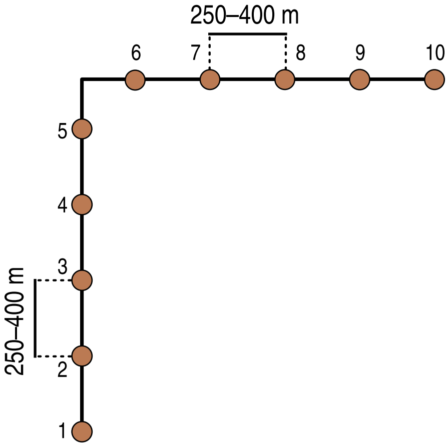


The location of the plots in a stratified design, Singida District



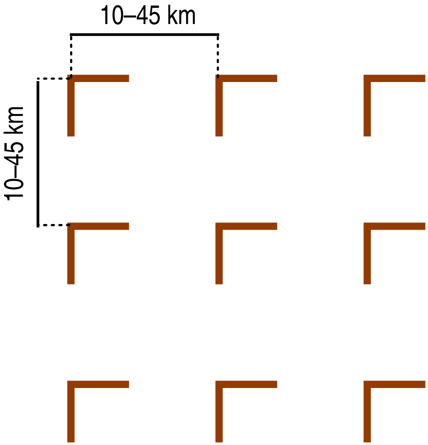
A field plot cluster, with plot distances tested for the design

A distance of 250 metres was confirmed with sampling studies



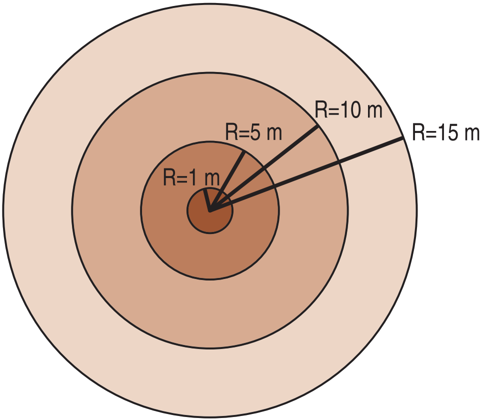
The clusters distances in the first phase sample was 5 km $\times$ 5 km

Examples of the cluster distances for the second phase sample



Field plot since May 2011, max radius 15 m

Tress with dbh $<$ 5 cm are measured on the permanent plots only



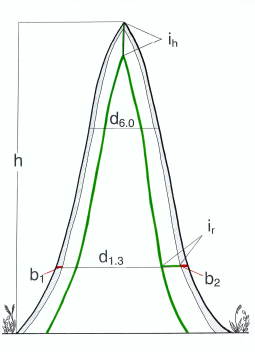
Species name and dbh of all measured trees will be recorded in each plot in the following manner

1) Within 1 m radius: all trees with dbh ≥ 1 cm will be recorded Only on permanent plots
2) Within 5 m radius; all trees with dbh > 5 cm will be recorded
3) Within 10 m radius; all trees with dbh > 10 cm will be recorded
4) Within 15 m radius; all trees with dbh > 20 cm will be recorded

Examples of plot variables

- ⟹ Land use, Vegetation type, Ownership
- ⟹ Canopy cover, Undergrowth
- ⟹ Damages and severity,
- ⟹ Soil data, Erosion, Grazing
- ⟹ Water catchment
- ⟹ Human impact
- ⟹ Non-wood forest products and services
- ⟹ Management proposals
- ⟹ Biodiversity

Examples of tally tree and sample tree measurements



- Species
- Diameter at 1.3 m above the ground level
- Total height, sample trees
- Bole length, sample trees

Estimation

- For large areas, Districts $\sim$ 1 million hectares, using field data only
- For small areas, villages, with multi-source inventory
- A possibility, post stratification based on map data / multi-source output maps

The first phase: volume estimate for each tree

- Height for tally tree, a simple model using sample tree measurements
  - $\hat{h} = a + b \times d + c \times d^2 + \epsilon$
- Volume
  - e.g., $\hat{v} = \pi \times (d/2)^2 \times \hat{h}$,
- In the continuation, more accurate volume models and by tree species groups

Demonstration of problems in measuring tree height / stem length and bole height?

Demonstration, ... tree height, cont.

Demonstration, ... tree height, cont.

Area estimates, field data

- Area estimates: land use classes, Vegetation types, tree species dominance, quality of forests, age distributions, accomplished and proposed measures, etc.
- Principles
  - Land area is assumed to be known, i.e., error free in Tanzania by Districts
  - The estimators are based on the numbers of plot centres

The estimator of the proportion of the forest area, e.g., is

$$\hat{P}_{F,c} = \frac{\sum_{i \in c} y_i}{\sum_{i \in c} x_i} \quad (1)$$

$i \in c$ means that the centre point of plot i is within region c

$y_i = 1$, when the centre point of the sample plot i is classified to be on forest land, 0 otherwise

$x_i = 1$, when the centre point of the sample plot i is on land, 0 otherwise

Area estimates, field data, cont

$\hat{P}_{F,c}$ can be written

$$\hat{P}_{F,c} = \frac{n_{F,c}}{n_c} \qquad (2)$$

$n_{F,c} =$ the number of the sample plot centres on forest land within region c
$n_c =$ the number of the sample plot centres on land within region c
Note that $\hat{P}_{F,c}$ is a ratio estimator, both the nominator and denominator are random variables.
It is thus a biased, but the bias is negligible.

Area estimates, field data, cont

The estimator of the *absolute area* $\hat{A}_{F,c}$

$$\hat{A}_{F,c} = \frac{n_{F,c}}{n_c} \times A_c \tag{3}$$

where A_c is the known land area of region c.
Each sample plot centre in region c is defined to represent an area a land area of

$$a_c = \frac{A_c}{n_c} \tag{4}$$

Estimation of the growing stock

Examples: mean and total volume, basal area, number of stems, mean diameter.

Formulas given through an example, Acasia trees on forest land.

Notations:

$N_{F,P,c} =$ number of Acasias on forest land (F) within region c

d_k = breast height diameter ($d_{1.3}$, cm) of the k'th Acasia within forest land in region c

$g_k = \pi(d_k/2)^2$ the basal area of the k'th Acasia (the cross-section assumed a circle)

$v_k =$ stem volume (m^3) of the k'th Acasia

$A_{F,c} =$ area of forest land within region c

Estimation of the growing stock, cont

The definitions of the stock parameters

$\bar{n}_{F,P,c} = \frac{N_{F,P,c}}{A_{F,c}}$ the number of trees per hectare

$\bar{d}_{F,P,c} = \frac{\sum_{k=1}^{N_{F,P,c}} g_k d_k}{\sum_{k=1}^{N_{F,P,c}} g_k}$ basal area weighted mean diameter (cm)

$\bar{g}_{F,P,c} = \frac{1}{A_{F,c}} \sum_{k=1}^{N_{F,P,c}} \frac{g_k}{10000}$ basal area (m^2/ha)

$\bar{v}_{F,P,c} = \frac{1}{A_{F,c}} \sum_{k=1}^{N_{F,P,c}} v_k$ mean volume(m^3/ha)

$V_{F,P,c} = \bar{v}_{F,P,c} A_{F,c}$ total volume(m^3)

Estimation of the growing stock, cont

Parameters $\bar{n}_{F,P,c}$, $\bar{g}_{F,P,c}$, $\bar{v}_{F,P,c}$ can be expressed in a general form

$$\bar{y}_{F,P,c} = \frac{1}{A_{F,c}} \sum_{k=1}^{N_{F,P,c}} y_k \tag{5}$$

where y_k is some characteristic of tree k.
In the case of the number of the trees, $y_k = 1$ for all trees k.

Estimation of the growing stock, cont

An arbitrary tree k is included as a tally tree if one of the sample plot centres is located within a circle, the origin of which is the location of tree k and the radius (m) equal to

$$r_k = r_{max,d_k} \tag{6}$$

where r_{max,d_k} is the maximum radius from which a tally tree k is measured, 1 (2), 5, 10 or 15 m

Estimation of the growing stock, cont

If the number of the field plot centres in a region with a land area of A_c is n_c, the plot density (the number of the plots per m^2) is $n_c/(10000 A_c)$ and the
the inclusion probability of an arbitrary tree k is

$$p_k = \frac{n_c}{10000 A_c} \pi r_k^2 \tag{7}$$

The what is called Horwitz-Thomson estimator for the sum in Eq. (5) is

$$\hat{y}_{F,P,c} = \sum_{k \in S} \frac{y_k}{p_k} = \sum_{k \in S} \frac{10000 A_c \, y_k}{n_c \pi r_k^2} \tag{8}$$

where S is the set of Acasia trees in the sample.

Estimation of the growing stock, cont

Using the estimator of Eq. 3 for the forest land area $A_{F,c}$ the mean value estimator is obtained

$$\hat{y}_{F,P,c} = \frac{n_c}{A_c n_{F,c}} \sum_{k \in S} \frac{10000 A_c y_k}{n_c \pi r_k^2} = \frac{10000}{n_{F,c}} \sum_{k \in S} \frac{y_k}{\pi r_k^2} \qquad (9)$$

Estimation of the growing stock, cont

When combining Eq. 6 and Eq. 9, $\hat{y}_{F,P,c}$ can be written

$$\hat{y}_{F,P,c} = \frac{10000}{n_{F,c}} \sum_{k \in S} \frac{y_k}{\pi r_k^2} = \frac{10000}{n_{F,c}} \sum_{k \in S} \frac{g_k}{b_k} \frac{y_k}{g_k} \tag{10}$$

where b_k is the area of a circle with a radius of r_k.

Estimation of the growing stock, cont

In the case of volume, we get, y_k/g_k = v_k/g_k = fh_k and is called the form height of a tree.
Using the form height, the estimator for the mean volume is

$$\hat{v}_{F,P,c} = \frac{10000}{n_F} \sum_{k \in S} w_k f h_k \tag{11}$$

where

$$w_k = g_k/b_k \tag{12}$$

The total volume estimator of the Acasia on forest land in the region c is

$$\hat{V}_{F,P,c} = \hat{v}_{F,P,c} \, \hat{A}_{F,c} \tag{13}$$

Applying to double sampling for stratification

Phases

- Estimate the areas of the strata for the calculation units, e.g., for Districts, using the first phase sample and known land areas
- Estimate the areas and volumes within each stratum using the methods given above
- Combine the estimates from the strata (assuming independence of the estimators in error estimation, see below)

Error estimation

Both area and volume estimators can be expressed as ratio estimators y_i and x_i be the observed values on the plot i, n the number of field plots in the region c with an area A_c.

$$m_c = \frac{\sum_i^n y_i}{\sum_i^n x_i} \qquad 15$$

For (11) the sum of numerator contains the volume of the pine trees. The error estimation is based on the variation of the cluster level residuals

$$z_r = y_r - m_c x_r$$

and

$$y_r = \sum_{i \in r} y_i$$

and x_r is defined similarly

Error estimation, cont

The design-based variance estimator can be estimated by

$$V(m_c) = \frac{V(\sum_{r \in c} z_r)}{(\sum_{r \in c} x_r)^2} \qquad 15$$

There are several ways to estimate the numerator, e.g., the quadratic forms (e.g., Matérn 1960). In the absence of a spatial trend, the cluster level residuals can be assumed independent and the numerator can be approximated by the sum of variances of the residuals.

Error estimation, cont

The standard approximation based on the delta method can be applied to obtain the variance of the total volume estimators:

$$V(\hat{V}_{l,P,c}) = V(\hat{v}_{l,P,c}\hat{A}_{l,c}) \approx v^2_{l,P,c}V(\hat{A}_{l,c}) + \hat{A}^2_{l,c}V(\hat{v}_{l,P,c})$$

Error estimation, cont

For aggregate regions C, double sampling in Tanzania, containing several regions or strata, the variances of the area estimators are estimated

$$V(\hat{A}_{l,c}) = \sum_{c \in C} V(\hat{A}_{l,c})$$

and those by volume estimators

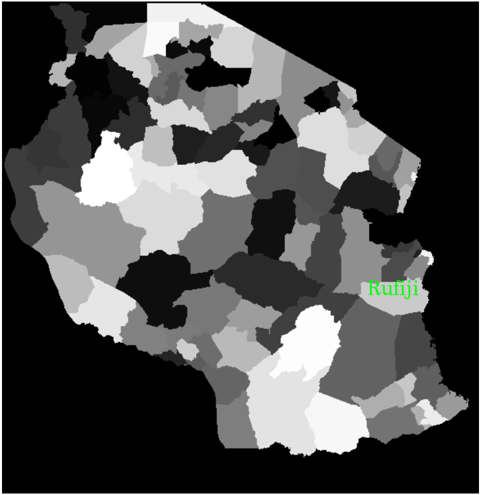
$$V(\hat{V}_{l,c}) = \sum_{c \in C} V(\hat{V}_{l,c})$$

.

and finally, the variance of the mean volume estimators for aggregate region C is estimated by

$$V(\hat{v}_{l,P,c})/\hat{v}^2_{l,P,c} \sim V(\hat{V}_{l,P,c})/\hat{V}^2_{l,P,c} - V(\hat{A}_{l,c})/\hat{A}^2_{l,c}$$

Tanzania and the Districts



Vegetation type categories

1 = Forest: Humid Montane, Lowland, Mangrove, Plantation
2 = Woodland: Closed (>403 = Bushland: Thicket, Dense, Scattered cultivation, Open
4 = Grassland: Wooded, Bushed, Scattered cropland, Ope
5 = Cultivated land: Agro-forestry system, Wooded crops, Herbaceous crops, Grain crops
6 = Open land: Bare soil, Coastal bare land, Rock outcrops, Ice-cap / snow
7 = Water: Ocean, 8 Water: Inland water, Water: Wetlands
8 = Other areas

Land use categories

1 = Production forest
2 = Protection forest
3 = Wildlife reserve
4 = Shifting cultivation
5 = Agriculture
6 = Grazing land
7 = Built-up areas
8 = Water body or swamp
9 = Other land

Table: Rufiji total area, land + water 13,339 km^2, National Bureau of Statistics (NBS) and COAST REGIONAL COMMISSIONER'S OFFICE Dar es Salaam, Tanzania, provided by Dr. Zahabu (Note: Rufiji, land + water = 1319577 ha, from Hunting map.)

	Vegetation type								
Land use	1	2	3	4	5	6	7	8	Total
1	34927	292108	8448	8574	0	0	32722	2479	379256
2	22863	68932	1006	4424	0	0	6071	0	103295
3	15858	245006	4077	21951	0	1012	327	0	288229
4	218	26897	8016	218	13133	0	0	0	48481
5	0	0	5281	44926	277850	0	0	4671	332726
6	0	26671	5316	1085	0	0	0	0	33071
7	0	0	0	0	0	0	0	97499	97499
8	436	0	0	0	0	0	8531	0	8966
9	0	7520	0	33253	0	0	0	1609	42381
Total	74299	667132	32143	114429	290983	1012	47649	106256	1333900

Relative errors for Vegetation type 1, 6.1%, Vegetation type 1+2, 2.6% Vegetation type categories 1+2+3, 2.5%

Table: Total volume (1000 m^3) by land use categories and vegetation type for Rufiji. NAFORMA 2011.

	Vegetation type								
Land use	1	2	3	4	5	6	7	8	Total
	1	2	3	4	5	6	7	8	Sum
1	2039	15009	406	4	-	-	162	7	17623
2	1516	3362	56	60	-	-	86	-	5078
3	1056	12987	90	24	-	0	0	-	14155
4	8	759	141	1	63	-	-	-	971
5	-	-	46	758	7078	-	-	16	7896
6	-	748	69	-	-	-	-	-	816
7	-	-	-	-	-	-	-	4589	4589
8	4	-	-	-	-	-	-	-	4
9	-	344	-	150	-	-	-	16	509
Sum	4621	33207	805	994	7141	0	247	4626	51638

- = not possible to estimate, e.g., no observations in the category

Relative volume errors (CV) Total volume 6.6% (of 51.638 mill. m^3)

Table: Mean volume (m^3/ha) by land use categories and vegetation type for Rufiji. NAFORMA 2011

	Vegetation type								
Land use	1	2	3	4	5	6	7	8	Total
1	58.37	51.38	47.99	0.35	-	-	4.93	2.43	46.5
2	66.30	48.77	54.74	13.44	-	-	14.13	-	49.2
3	66.53	53.01	21.93	1.06	-	0	0.00	-	49.1
4	34.76	28.20	17.57	3.59	4.79	-	-	-	20.0
5	-	-	8.54	16.86	25.47	-	-	3.25	23.7
6	-	28.03	12.88	-	-	-	-	-	24.7
7	-	-	-	-	-	-	-	47.07	47.2
8	7.15	-	-	-	-	-	-	-	0.4
9	-	45.69	-	4.50	-	-	0.00	9.46	12.0
Total	62.18	49.78	25.02	8.68	24.54	0	5.18	43.53	38.7

- = not possible to estimate, e.g., no observations in the category
Relative volume errors (CV), Mean volume 6.3% (of 38.71 m^3/ha)

Table: Mean volume (m^3/ha) by land use categories and vegetation type for Rufiji, dbh at least 20 cm. NAFORMA 2011.

	Vegetation type								
Land use	1	2	3	4	5	6	7	8	Total
1	37.18	40.81	37.70	0.00	-	-	4.90	0.00	36.1
2	41.61	36.08	42.81	7.78	-	-	14.06	-	34.9
3	49.83	40.32	20.97	0.46	-	0	0.00	-	37.4
4	0.00	14.61	9.32	2.45	4.131	-	-	-	10.8
5	-	-	6.96	14.62	22.782	-	-	0.15	21.1
6	-	17.14	11.20	-	-	-	-	-	15.6
7	-	-	-	-	-	-	-	39.87	39.9
8	0.00	-	-	-	-	-	-	-	0.0
9	-	38.80	-	3.28	-	-	0.00	10.16	9.8
Total	40.92	38.11	19.23	7.09	21.930	-	5.16	36.74	30.3

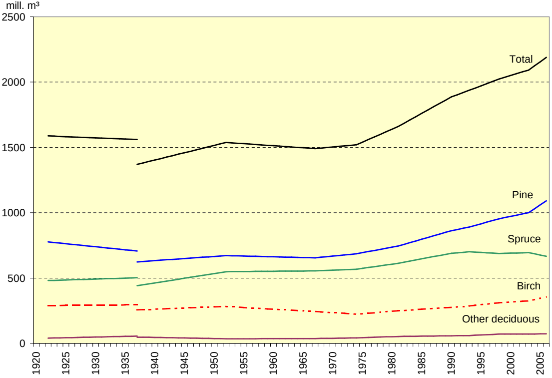
- = not possible to estimate, e.g., no observations in the category CV for 30.31 m^3/ha, 7.7%

Table: Number of trees per hectare (stems/ha), dbh $>$ 1 cm by land use categories and vegetation type for Rufiji. NAFORMA 2011.

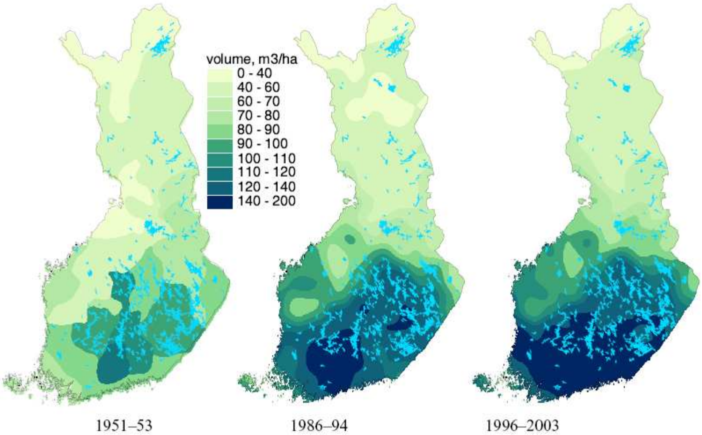
	Vegetation type								
Land use	1	2	3	4	5	6	7	8	Total
1	3145.78	1272.72	1894.60	5.56	-	-	33.64	1626.88	1326
2	3335.49	1591.14	771.02	14352.24	-	-	319.00	-	2441
3	4993.94	1301.92	252.43	176.22	-	0	0.00	-	1398
4	6907.32	5484.95	2820.93	2792.29	643.231	-	-	-	3727
5	-	-	982.55	97.58	630.772	-	-	300.32	560
6	-	1293.13	600.64	-	-	-	-	-	1139
7	-	-	-	-	-	-	-	275.92	276
8	2944.37	-	-	-	-	-	-	-	143
9	-	817.01	-	497.88	-	-	-	21.22	536
Total	3608.44	1481.85	1518.32	777.38	631.330	-	63.74	304.65	1210

- = not possible to estimate, e.g., no observations in the category CV for 1209.66 stems/ha 9.6%

An example from Finland, Volume of growing stock 1921 - 2006, Forest and other wooded land



An example from Finland, The volume of growing stock in 1951-53, 1986-94 and 1996-2003, field data and Kriging interpolation



Conclusions

- A new approach for the sampling design was introduced, a double sampling for stratification
- The estimators have to be derived similarly
- A key information source for national and regional decision making
- A key information source for international reporting, including REDD+ MRV

Examples of publications

Tomppo, E., Heikkinen, J., Henttonen, H., Ihalainen, A., Katila, M., Mäkelä, H., Tuomainen, T., Vainikainen, N. 2011. Designing and conducting a forest inventory - case: 9th National Forest Inventory of Finland. Managing Forest Ecosystems 22. Springer. 305 p. ISBN 978-94-007-1651-3.

Heikkinen, J. 2006. Assessment of uncertainty in spatially systematic sampling. In: Kangas, A. & Maltamo, M. (eds.). Forest inventory. Methodology and applications. Managing Forest Ecosystems. Vol 10. Springer, Dordrecht. p. 155-176.

Tomppo, E., Gschwantner, Th., Lawrence, M. & McRoberts, R.E. (eds.) 2010. National Forest Inventories - Pathways for common reporting. Springer, 612 p. ISBN 978-90-481-3232-4.

Examples of publications, cont

Cochran, W. G. 1977. Sampling techniques. 3rd ed. New York, Wiley
Matér, B. 1960. Spatial variation. Meddelanden från statens skogsforskningsinstitut, 49:1-144. Also appeared as Lecture Notes in Statistics 36. Springer-Verlag. 1986.
Ilvessalo, Y. 1927. The forests of Suomi Finland. Results of the general survey of the forests of the country carried out during the years 1921-1924. (In Finnish with English summary). Communicationes ex Instituto Quaestionum Forestalium Finlandie 11.
Tomppo, E. 2006. The Finnish National Forest Inventory. In: Kangas, A. & Maltamo, M. (eds.). Forest inventory. Methodology and applications. Managing Forest Ecosystems. Vol 10. Springer, Dordrecht. p. 179-194.
Tomppo, E., Haakana, M., Katila, M., Peräsaari, J. 2008. Multi-Source National Forest Inventory Methods and Applications Springer, Series: Managing Forest Ecosystems , Vol. 18 374 p. Hardcover. ISBN: 978-1-4020-8712-7.