Original Research Article

EVALUATING EFFICIENCY OF SAMPLING SCHEMES IN TROPICAL NATURAL FORESTS: REVIEW AND SIMULATION EXPERIENCE FROM KENYA

ABSTRACT

Forest measurements, especially in natural forests are cumbersome and complex. 100% enumeration is costly and inefficient. This study sought to find out reliable, efficient and cost-effective sampling schemes for use in tropical rain forest (TRF), moist montane forest (MMF) and dry woodland forest (DWF) in Kenya. Fourty-eight sampling schemes (each combining sampling intensity (5, 10, 20, 30%), plot size (25, 50, 100, 400 m^2) and sampling technique (simple random sampling, systematic sampling along North-South and along East-West orientations) were generated for testing estimates of forest attributes such as regeneration through simulation using R-software. Sampling error and effort were used to measure efficiency of each sampling scheme in relation to actual values. Though forest sites differed in biophysical characteristics, cost of sampling increased with decreasing plot size regardless of the forest type and attribute. Accuracy of inventory increased with decreasing plot size. Plot sizes that captured inherent variability were 5mx5m for regeneration and trees ha^{-1} across forest types but varied between forest types for basal area. Different sampling schemes were ranked for relative efficiency through simulation techniques, using regeneration as an example. In many instances systematic sampling-based sampling schemes were most effective. Sub-sampling in one-hectare forest unit gave reliable results in TRF (e.g. SSV-5mx5m-30%) and DWF (e.g. SSV-10mx10m-30%) but not in MMF (5mx5m-100%). One-hectare-complete-inventory method was found inevitable for regeneration assessment in montane forest.

Key words: forest measurement, optimum plot size, inventory protocol, regeneration assessment

1. INTRODUCTION

Assessments of tropical natural forests are often constrained by lack of sampling protocols of known reliability. Different plot sizes, sampling intensities, sampling techniques have been applied in mixed tropical forests with no indication of the efficiency or quality of methods used. Existing single-level sampling designs commonly applied in forestry include spatial random or systematic distribution of sampling units [e.g.1,2]. However, systematic sampling is the most practiced due to logistical advantages over random sampling, despite some statistical weaknesses [1,2,3,4]. In practice, it is advised to randomize the starting plot and apply systematic distribution of the others [1,2,3]. Multistage sampling techniques, stratification and cluster sampling are known to increase efficiency in forest inventory [3, 5]. Past studies suggest that a plot size of one hectare is a suitable as a sampling unit [e.g., 3]. Smaller plots have been adopted in some forest vegetation studies [e.g. 6,7]. In vegetation studies, fewer but larger plots are documented to perform better than many but small plots; but there is always need to strike a balance between the cost and precision or accuracy when fixing the required sampling intensity [6]. Although subdividing any forest estate into 1-ha-inventory units is a common and agreeable practice, this study was designed to explore whether or not there could be any opportunity to sub-sample this standard unit to reduce the cost of inventory, and at the same time, achieve statistically similar or higher accuracy of estimates on-per-hectare basis.

This paper reports findings on evaluation of efficiency of sampling schemes in tropical natural forests based on data from typical tropical forests and woodlands in Kenya, simulated sampling designs to capture such data and existing literature. The study was conceived based on the premises that: (i) Forest assessment studies are complex in the context of tropical mixed natural forests and in the wake of changing roles of forests and tree resources due to dynamic socio-ecological and economic situations; (ii) there are many research initiatives undertaken in forest resources assessment, but studies on efficiency and harmonization of sampling methodologies in forestry are rare; (iii) natural forests and woodlands are today recognized as critical assets for livelihoods sustenance for many people, biodiversity conservation, economic development and climate moderation for which quality information is mandatory in order to guide strategic and management plans; however, there is lack of scientifically tested and locally adapted tools to be used in generating the much needed knowledge for those complex and diverse ecosystems; and (iv) based on the existing knowledge in forest sampling techniques, on past practices in forest assessments as well as the current computer technologies, research on efficiency of sampling schemes (accuracy, precision and cost) is achievable. A research was designed seeking to fill the aforementioned gaps by seeking to establish optimum sampling schemes for selected forest attributes with known accuracy and precision. In this context, a sampling scheme is a framework integrating specific sampling design, intensity and plot size. The approach was deductive, starting from the known situation (true population parameters) to generate scientific approximations (estimated population parameters) through a range of statistical procedures. It was hypothesized that sampling efficiency (accuracy and precision) for regeneration, species diversity and forest structure differed among individual sampling schemes across forest types, and varied with plot sizes and sampling intensities.

1.1 Review of sampling experiences and efficiency in natural forests

Field studies through sampling are often combined with most commonly used remote sensing technologies to accelerate assessment of forest resources [3,10, 11, 12, 13, 14, 15]. Commonly used field sampling techniques in tropical forest ecosystems include walk trails, transects and plots to characterize tree species diversity, vegetation types, wildlife richness, forest structure and regeneration [13, 16] as well as to study allometric relationships for modelling forest growth and yield including evaluation of site quality [17, 18]. Vegetation sampling strategies in tropical forests are dictated and challenged by such factors as ragged terrain, abundant wildlife, expansiveness of the area and scarcity of baseline data e.g. checklists of indigenous species.

Different researchers in Kenya have used varied plot sizes, e.g. 20 m x 10 m [13, 19], 10 m x 10 m [20]. In addition, sub-sampling using nested smaller plots within the large units is often applied in assessing forest regeneration and other plot features [12, 21, 22]. Saplings and seedlings are counted from different sub-plot sizes e.g. 40 m^2 and 20 m^2, respectively. The above sampling approach enables the collection of useful information on multiple attributes from forests in a short time. The collected plot-level data reveal actual state of forest conditions e.g. regeneration, recruitment, structure, diversity, disturbances [12, 23, 24, 25, 26, 27, 28]. Integrating use of aerial photographs and field sample plots along altitudinal changes provides data for the description of montane forest vegetation [e.g., 29]. In summary, a mix of different plot shapes, plot sizes and sampling intensities have been applied in different studies in forestry but at the subjective will of different reseachers and with no justification nor indication of any possible impact such mix would have on the reliability (accuracy and precision) of the findings. Ecological and socioeconomic factors are increasingly becoming important in contemporary forestry in addition to forest biophysical attributes [30, 31]. The emerging new demands dictate the need to develop tools to collect adequate data efficiently and generate required knowledge to guide sustainable management [22, 32]. To capture quality data from natural forests, different tools and methods commonly used in forest inventory must be well combined [33] and planners and managers of forests and allied resources must have the ability to identify suitable methods to produce the needed data.

2. MATERIALS AND METHODS

2.1 Study sites

Three selected sites in tropical natural forests of Kenya: Kakamega tropical rain forest (TRF) (34º54'3.078" - 34º54'6.318"N, 0º16'10.646" - 0º16'13.882"E), Mount Elgon moist montane forest (MMF) (34º41'31.319" - 34º41'34.555"N, 0º52'2.65" - 0º52'5.887"E) and Loruk dry woodland forest (DWF) (36º00'3.539" - 36º00'6.775"N, 0º42'36.884" - 0º42'40.121"E) were used to develop evaluation protocol for evaluation of sampling efficiency in complex forests. Figure 1 shows studied forests and sites. These forests reflect environmental gradients (climatic, topographic and anthropogenic disturbance); from low rainfall dry vegetation zone to high rainfall humid zone and lower montane moist forest zone (Table 1).

Table 1: Location, Elevation and Climate Characterising Study Sites in Kenya, 2019

Features		**TRF – Kakamega forest site**	**MMF - Mt. Elgon forest site**	**DWF –Loruk Dry woodland Site**
i.	Mean rainfall (mm yr^{-1})	1971-2000	1460–1622	629
ii.	Wettest month (mm)	January (61)	May (231).	May (92)
iii.	Driest month (mm)	May (273)	January (41)	February (21)
iv.	Altitude (m a.s.l.)	1580	2000-2060	987
v.	Mean annual temperature	20.4 ℃	15.2–18.0 ℃	23.7 ℃
vi.	Average warmest month	February (21.3℃)		March (24.8℃)
vii.	Average coldest month	July (19.3℃)		August (22.5 ℃).
viii.	Disturbance history	Moderate logging	Extensive Logging	Livestock grazing
ix.	Climate type	*Tropical Humid and warm*	*Temperate Moist and warm*	*Dry* Tropical climate

Sources: [12, 25, 34, 35, 36, 37]. Weather data are averages between 1982 and 2012.

2.2 Field methods

2.2.1 Forest unit of reference

From inside each forest, a one-hectare (100 m x 100 m) forest unit was selected, at least 500 m from forest edge. It was referred to as forest unit of reference and represented the "studied populations" for different forest attributes of interest. Field data from these units were used as "controls" against which relative efficiency of each of the sampling schemes was compared and evaluated. The one-hectare unit was subdivided into smaller units during field data collection as illustrated in Figure 2.

2.2.2 Field work organization

Data collection over 1-ha forest unit of reference was done in the field to determine "true" values of forest attributes. It was achieved by establishing 10 m x 10 m temporal field plots to be subdivided into four 5 m x 5 m subplots to ensure accurate field observations of forest attributes from seedling stage were made and recorded. Complete enumeration of forest attributes was carefully and systematically done in four hundred 5 m x 5 m smallest units of data compilation. To enhance accuracy of observations on small sized individuals of the regeneration (seedlings), search and counts were done within 1mx1m-subplots, one after the other, within the 5mx5m-plot. Pre-prepared field data collection sheets were used and filled manually by trained field assistant. The labelling was done for each 5mx5m-plot with an identification number for easy retrieval (see illustration in Figure 2). The largest plot size we tested in the sampling study was 20 m x 20 m. Each data entry was linked to a uniquely coded 5 m x 5 m plot. Data for plots larger than 5 m x 5 m were obtained through computer simulation using R Software by collapsing boundaries and merging adjacent smaller plots as applicable: from 5mx5m-plots, 5mx10m and 10mx10m-plots were formed. Merging adjacent 10mx10m-plots formed 20mx20m-plots. Merging of smaller plots was automatically associated with collating records they contained. Sums, averages and other computations were done for different plot sizes using R software modules. Similar data would otherwise be obtained in practice from field activity.

2.2.3 Sampling designs

Sampling design or method is the pattern of distribution of sampling units over the sampling frame. Three basic designs were tested in each forest type: Simple random sampling (SRS), systematic sampling along vertical transect facing North – South direction (SSV), and systematic sampling along horizontal transect facing East – West direction (SSH). The number of plots sampled in each design varied depending on the plot size and sampling intensity (Table 2).

2.2.4. Sampling frame, sampling schemes designing and administration

The sampling frame was made of the sampling units i.e. plots in the one-hectare forest unit of reference. Population size (N) varied between 25 and 400 depending on the plot size: 400, 200, 100 and 25 units for 5 m x 5 m, 10 m x 5 m, 10 m x 10 m and 20 m x 20 m plot size, respectively. A sampling scheme was defined by the combination of three elements: sampling design, sampling intensity and plot size. Each scheme was applied and evaluated for efficiency (combining accuracy, precision and cost) on each forest type. Sampling was performed on each pupulation of selected attributes in the forest unit of reference, applying 48 simulated sampling schemes through R Software (Table 2). Real time data were collected from the field. Relative accuracy and efficiency of random and systematic sampling designs integrated with four plot sizes (25, 50, 100, 400 m^2) and four intensities (5, 10, 20, 30%) were investigated with reference to full-cover one-hectare inventory in each studied forest type.

2.3. Assessed forest variables and derived attributes

Key attributes of interest included components of forest structure, composition and regeneration which are of high ecological, silvicultural and conservation significance [12, 38, 39]. Forest canopy height was measured to the nearest m from each 5mx5m-plot using suunto hypsometer [1, 4]. Tree diameters at breast height [4,18] were measured using callipers to the nearest mm and cm for saplings and trees, respectively. Light screening efficiency in the forest was determined at the plot centre, using a 1m x 1m transparent polythene fixed on a wooden frame and subdivided in 100 square grid, [40, 41]. A canopy gap unit was any space measuring 5 m x 5 m or more, devoid of tree canopy cover. Trees were identified to species level using dendrology documentation [e.g. 42], existing checklists [13, 36, 41] or local parataxonomists. No material was collected from the forests. Effort taken to complete inventory fieldwork within a plot was recorded in minutes [43], using a watch chronometer. For each 5mx5m-plot, tree seedling counts were done systematically and tallied progressively from 1mx1m-subplots. A field team of 4-people (supervisor, skilled technical staff and two field assistants) was used. Field measurements and observations were later entered and organised in MS Excel 2010 and IBM SPSS Statistics version 21 before exporting and analysis in R version 3.4.4.

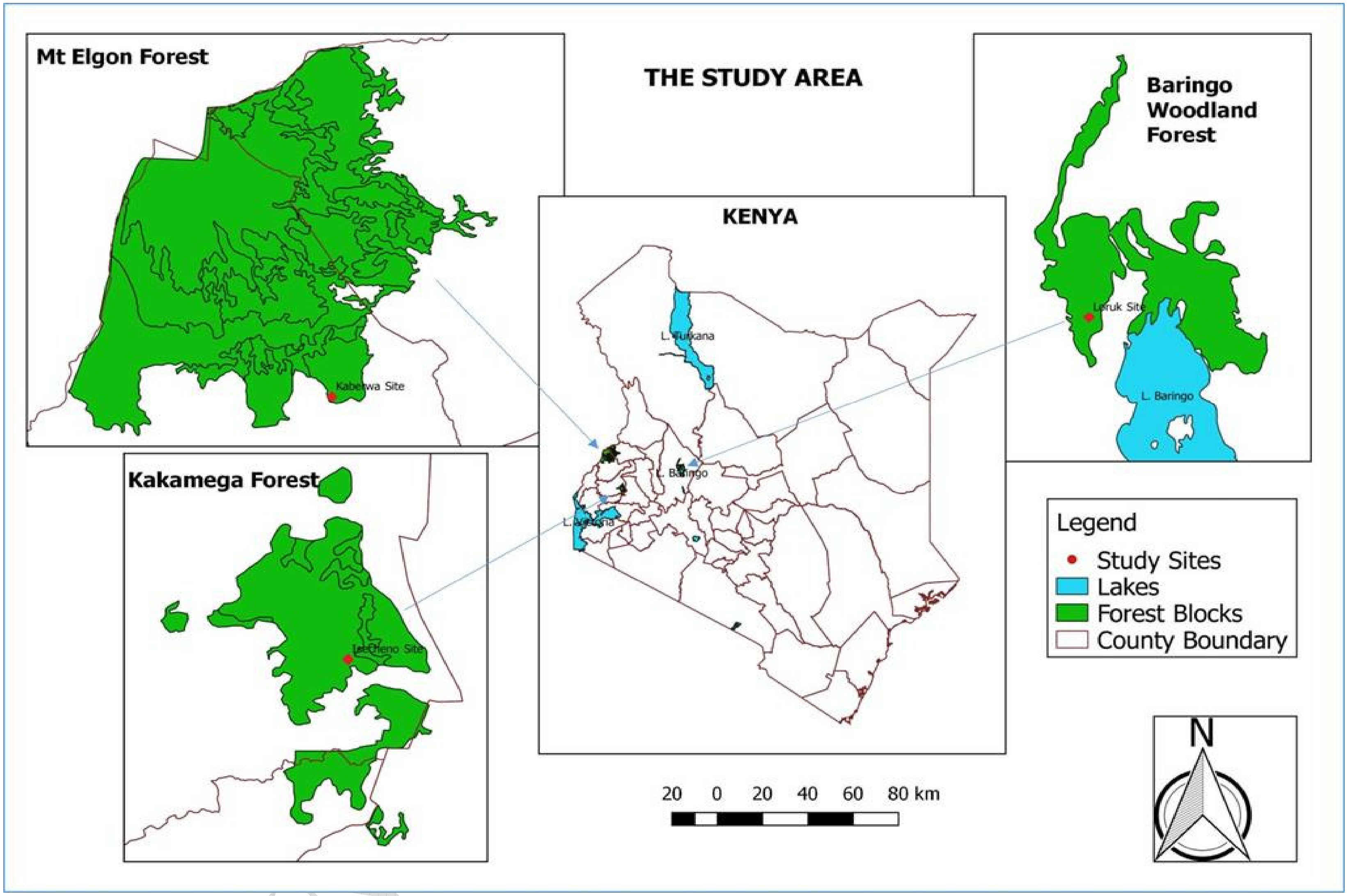
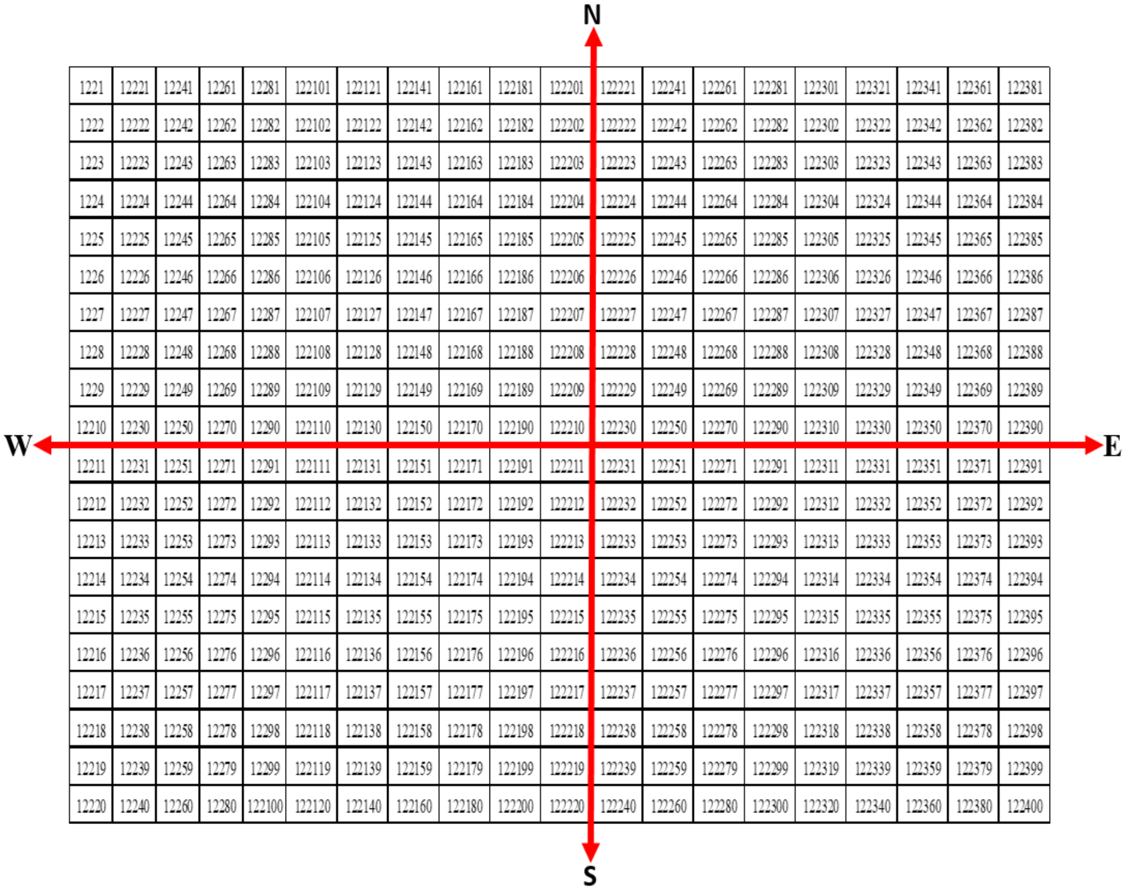


Figure 1: Location of Study Sites in Kenya, 2019



1221	12221	12241	12261	12281	122101	122121	122141	122161	122181	122201	122221	122241	122261	122281	122301	122321	122341	122361	122381
1222	12222	12242	12262	12282	122102	122122	122142	122162	122182	122202	122222	122242	122262	122282	122302	122322	122342	122362	122382
1223	12223	12243	12263	12283	122103	122123	122143	122163	122183	122203	122223	122243	122263	122283	122303	122323	122343	122363	122383
1224	12224	12244	12264	12284	122104	122124	122144	122164	122184	122204	122224	122244	122264	122284	122304	122324	122344	122364	122384
1225	12225	12245	12265	12285	122105	122125	122145	122165	122185	122205	122225	122245	122265	122285	122305	122325	122345	122365	122385
1226	12226	12246	12266	12286	122106	122126	122146	122166	122186	122206	122226	122246	122266	122286	122306	122326	122346	122366	122386
1227	12227	12247	12267	12287	122107	122127	122147	122167	122187	122207	122227	122247	122267	122287	122307	122327	122347	122367	122387
1228	12228	12248	12268	12288	122108	122128	122148	122168	122188	122208	122228	122248	122268	122288	122308	122328	122348	122368	122388
1229	12229	12249	12269	12289	122109	122129	122149	122169	122189	122209	122229	122249	122269	122289	122309	122329	122349	122369	122389
12210	12230	12250	12270	12290	122110	122130	122150	122170	122190	122210	122230	122250	122270	122290	122310	122330	122350	122370	122390
12211	12231	12251	12271	12291	122111	122131	122151	122171	122191	122211	122231	122251	122271	122291	122311	122331	122351	122371	122391
12212	12232	12252	12272	12292	122112	122132	122152	122172	122192	122212	122232	122252	122272	122292	122312	122332	122352	122372	122392
12213	12233	12253	12273	12293	122113	122133	122153	122173	122193	122213	122233	122253	122273	122293	122313	122333	122353	122373	122393
12214	12234	12254	12274	12294	122114	122134	122154	122174	122194	122214	122234	122254	122274	122294	122314	122334	122354	122374	122394
12215	12235	12255	12275	12295	122115	122135	122155	122175	122195	122215	122235	122255	122275	122295	122315	122335	122355	122375	122395
12216	12236	12256	12276	12296	122116	122136	122156	122176	122196	122216	122236	122256	122276	122296	122316	122336	122356	122376	122396
12217	12237	12257	12277	12297	122117	122137	122157	122177	122197	122217	122237	122257	122277	122297	122317	122337	122357	122377	122397
12218	12238	12258	12278	12298	122118	122138	122158	122178	122198	122218	122238	122258	122278	122298	122318	122338	122358	122378	122398
12219	12239	12259	12279	12299	122119	122139	122159	122179	122199	122219	122239	122259	122279	122299	122319	122339	122359	122379	122399
12220	12240	12260	12280	122100	122120	122140	122160	122180	122200	122220	122240	122260	122280	122300	122320	122340	122360	122380	122400

Figure 2: Example of field arrangement for four hundred 5mx5m-subplots in the 100mx100m-forest unit (Horizontal: E-W; Vertical: N-S), 2019.

Each cell with a number represent a coded 5mx5m-plot for easy data set identification, entry, storage, retrieval and use in sampling simulation activity. First three digits denote the forest site (122-Kakamega; 111-Mt Elgon; 131- Loruk). The subsequent digits represent serial plot number within the 100 m x 100 m frame.

Table 2. Sample sizes and distribution of sample plots among different sampling schemes, 2019

Sampling Design	Sampling intensity (n /N %)[1]	Plot sizes 5 m x 5 m (25 m^2)	10 m x 5 m (50 m^2)	10 m x10 m (100 m^2)	20 m x 20 m (400 m^2)
SRS	5	20	10	5	1
	10	40	20	10	2
	20	80	40	20	5
	30	120	60	30	7
SSH	5	20	10	5	1
	10	40	20	10	2
	20	80	40	20	5
	30	120	60	30	7
SSV	5	20	10	5	1
	10	40	20	10	2
	20	80	40	20	5
	30	120	60	30	7

SRS = Simple random sampling; SSH = Systematic plot sampling along horizontal transect;
SSV = Systematic plot sampling along vertical transect;
[1]n = sample size (no. of sample plots selected from one-hectare forest unit);
N = population size (total number of plots in a one-hectare forest unit)
A factorial combination of sampling design (3 levels), sampling intensity (4 levels) and plot sizes (4 levels) defined the 48 sampling schemes that were tested and compared for their efficiency.

2.4. Data analysis

Mean canopy height, % skylight through forest canopy, % forest 25m^2-gaps, mean slope % [41], basal area derived from tree diameters, number of trees ha^{-1}, quadratic mean diameter from basal area [5, 8, 21], tree species richness and Shannon-Wiener diversity index [14,39,41] were computed to characterize the study sites.

Inherent variability of the population of reference was measured by population mean variance for regeneration, trees and basal area ha^{-1}, based on different plot sizes (Eq. 1). The smallest mean variance for each attribute and forest type indicated a suitable plot size to be used in benchmarking efficiency of sampling schemes in terms of capturing inherent variability of studied populations.

Population mean variance = $\frac{\sigma^2}{N}$ …………………..(Eq. 1)

where, σ^2 = population variance; N = Total number of plots per ha which varied with plot size.

Cost and precision of different sampling schemes were expressed on-per-hectare basis for forest attributes of interest. Sample variance and standard error of mean (SE) (Eq. 2) were computed before the calculation of sampling error % (Eq. 3) [3, 44, 45, 46,47], also referred to as uncertainty level [6]. The smaller the uncertainty around the sample mean, the more precise the sampling scheme. Similarly, the smaller the uncertainty is around a population parameter estimate, the more accurate the inventory protocol. Any sampling scheme associated with uncertainty level less than 25% was considered to have acceptable precision and therefore was a promising scheme. Cost-efficiency of sampling schemes was measured based on the sampling effort. Efficiency level of a sampling scheme combined the cost factor, uncertainty level and ability of the scheme to estimate inherent variability of the population of reference. Using forest regeneration as an example, relative efficiency of different sampling schemes was computed based on cost, precision and accuracy (Eq. 4). Ranking of sampling schemes in terms of efficiency was graphically displayed.

SE = ${}^{s}/{\sqrt{n}}$ ……………………………………………………………(Eq. 2)

Where s = sample variance for the sampling scheme; n = sample size

Sampling error % =uncertainty % = $\frac{SE\times t}{\bar{X}}\times 100$ ……………………… (Eq. 3)

Where t = Student's t value obtained for each sample size from t-table with α = 0.05.

Efficiency % = $\frac{\sigma_1^2\times\frac{C_t}{N_1}}{S_1^2\times C_1/n_1}\times 100$…………………………………..………… (Eq. 4)

Where S_1^2 = sample variance for the sampling scheme;
n_1 = sample size (no. plots); C_1= hours spent on measuring variables (ie sampling effort or cost ha^{-1});
σ_1^2 = population variance of reference for the variable of interest;
C_t = actual total cost of measuring variables in one-hectare forest unit of reference;
N_1 the population size (number of plots per ha, varying with plot size).

The screening of schemes led to the characterisation of sampling protocols that minimise sampling error to enhance accuracy [44]. A desired precision level (uncertainty %) was set to be ≤ 25% which is adequate for inventories targeting multiple attributes, e.g. in tropical forests [44, 47].

3. RESULTS AND DISCUSSION

3.1 Evaluating efficiency of sampling schemes for forest structure studies

3.1.1 Biophysical characterization of reference forest populations

The forest populations of reference were characterised by environmental and biological attributes as shown below (Table 3). Tropical rainforest was distinctly the most complex and dry woodland forest the simplest ecosystems. Efficiency levels of sampling schemes were compared for each assessed attribute and forest type.

3.1.2 inherent variability of forest populations of reference

The 5mx5m plot size enable the measurement of variability for regeneration and trees in the three forest types (Table 5). Relative complexity of the forests based on this parameter was highest in the tropical rain forest and lowest in dry woodland forest. Assessment of inherent variability in basal area requires different plot sizes across forest types: largest (20mx20m) for MMF, 10mx10m for TRF and smallest (5mx5m) for DWF. It implies that large diameter trees are more scattered in Mt Elgon forest than in other forests, thus requiring larger plot size to capture inherent variability. Nested subplots (Figure 3) can accommodate simultaneous assessment of regeneration, trees and basal area within 1-hectare-forest unit, with each forest type having a distinct design as shown.

Table 3: Biophysical characterization of forest populations of reference, 2019

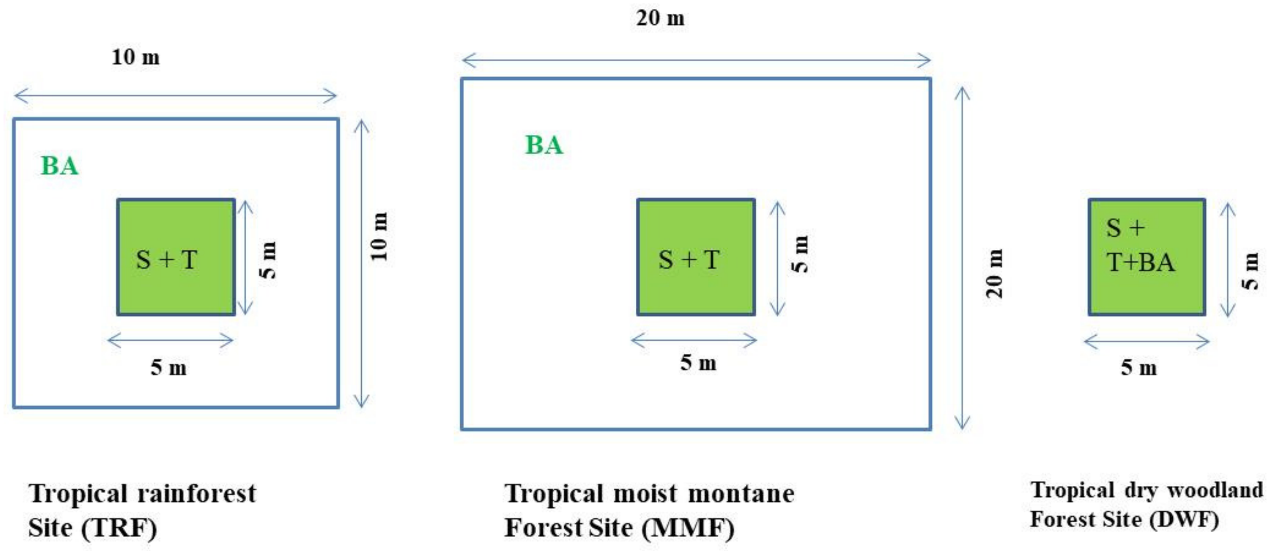
Forest type	Height (m)	% skylight through canopy	% Forest gaps	Tree QMD	N trees ha^{-1}	N Saplings ha^{-1}	N Seedlings ha^{-1}	Basal area (m^{2}h^{-1})	N tree species ha^{-1}	Species diversity	Mean slope %
TRF	31	26	0.8	14	1,166	2,684	15,598	68.8	54	3.3	0.1
MMF	23	38	0.8	13	816	5,463	1,432	25.1	37	2.7	9.5
DWF	5	71	9.0	4	299	795	2,275	2.1	12	1.8	0.0

Key:

QMD = Quadratic mean diameter in cm;
Tree = individual with ≥5 cm Dbh;
Sapling = individual with 1-5 cm Dbh;
Seedling = individual < 1 cm Dbh;
H' = Shannon Wiener index

Table 4: Population mean variance for selected forest attributes in complete inventory of a one-hectare-forest unit of reference, 2019

Attribute	Forest type	Smallest σ^2/N (variability)	Inventory cost		Data compilation unit (m x m)
			ha hr^{-1}	Hrs ha^{-1}	
Seedlings ha^{-1}	TRF	1,726,559.16	0.02	50	5x5
	MMF	223,003.91	0.02	50	5x5
	DWF	3,033.49	0.04	25	5x5
Stand density ha-1	TRF	5,239.46	0.02	50	5x5
	MMF	2,848.56	0.02	50	5x5
	DWF	2,427.01	0.04	25	5x5
Basal area / ha	TRF	46.97	0.08	12.5	10x10
	MMF	7.15	0.41	2.4	20x20
	DWF	0.05	0.04	25	5x5



Tropical rainforest Site (TRF)

Tropical moist montane Forest Site (MMF)

Tropical dry woodland Forest Site (DWF)

Figure 3. Plot sizes and lay outs for simultaneous inventory of seedlings, trees and basal area in 1 ha – forest unit with minimization of inherent population variability as a controlling factor for each attribute: S = seedlings counts (< 1 cm dbh); T = trees counts (> 1 cm dbh); and BA = Basal area (m^2 ha^{-1})] in Tropical rain forest, Moist montane forest and Dry woodland forest in Kenya.

3.1.3 Cost and precision of different sampling schemes: case of regeneration assessment

Figure 4 shows that precision in assessing seedlings per hectare increased with decreasing plot size. The decrease in precision and accuracy of estimates as plot size increases followed similar linear patterns for MMF and DWF. The decrease in reliability of estimates as a result of increasing plot size was more prominent and higher in TRF than in the other two forest types. Sampling effort increased with decreasing plot size (Figure 5). With 100% sampling intensity, larger plot sizes led to cheaper inventory in each forest type.

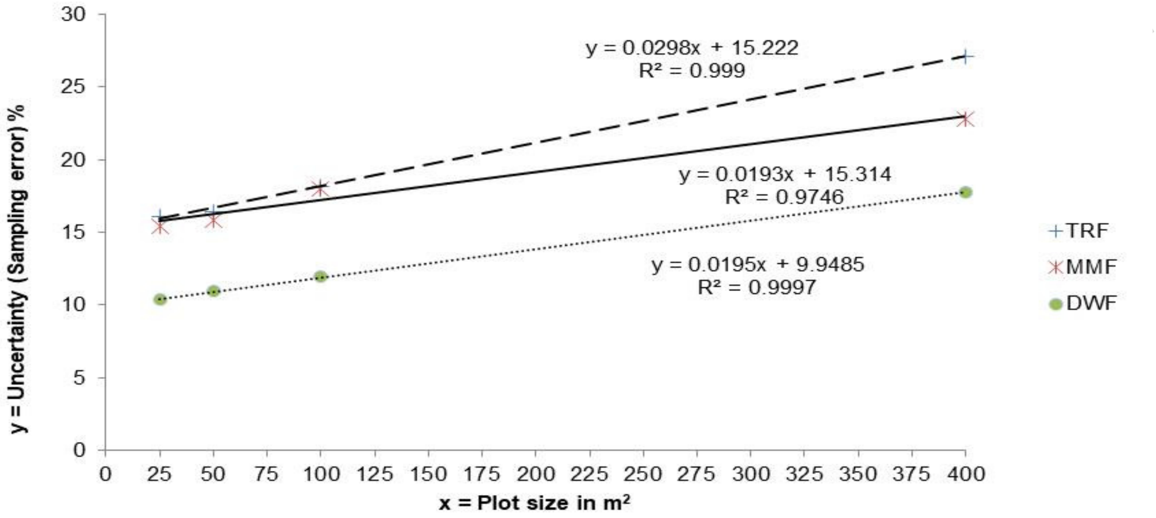


Figure 4: Effect of plot size on precision level in forest inventory (e.g. seedlings at 100 % intensity)

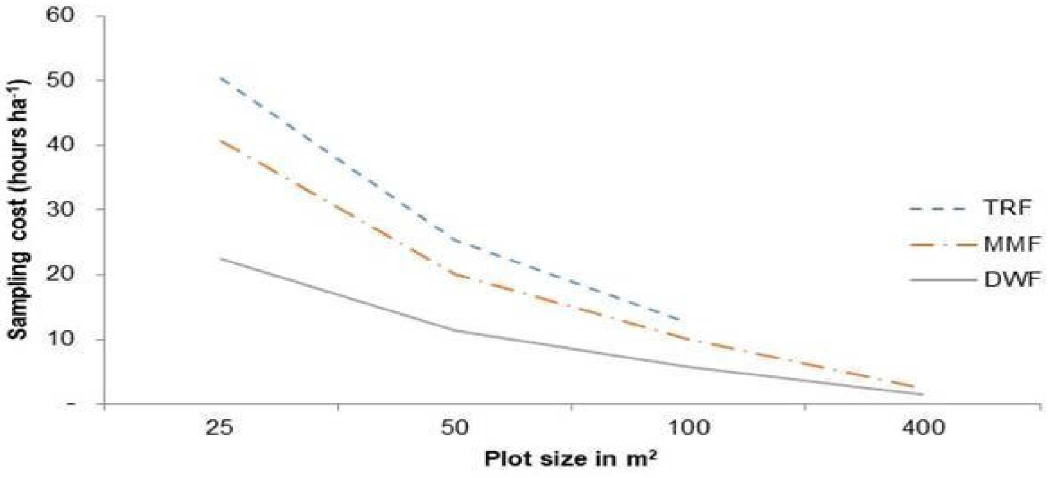


Figure 5. Relationship between sampling effort and plot size with complete forest inventory of number of seedlings ha^{-1} in different forest types (Tropical rainforest –TRF, Moist montane forest – MMF and Dry woodland forest – DWF)

Table 5 contains uncertainty and cost-efficiency associated with different sampling schemes for regeneration:

- Most reliable sampling protocol in TRF was systematic sampling along transects facing north-south with 25 to 50 m^2 plot sizes, and 30 % sampling intensity (95% CI uncertainty level < ± 25%). The cost of the larger plot was 50% lower. Therefore, SSV-5mx10 m-30% qualified as the most cost-efficient reliable sampling scheme.

- In the dry woodland forest, sub-sampling one hectare unit can use either random or systematic sampling (95% CI uncertainty of ± 15% to ± 25%). However, SSV/SSH-5mx10m-30% would be the most preferred over random sampling due to practical field advantages associated with systematic sampling [2]..

- In MMF, to achieve uncertainty of <25% requires complete inventory (100 % intensity). The most reliable and cost-efficient sampling protocol for seedlings is using 100m x 100m forest plot subdivided into 100 10mx10m-subplots. Sub-plot size influences cost and uncertainty .The 20 mx20 m sub-plot appears cheapest but the 10mx10m one strikes the best balance between precision and cost.

Table 5: Forest inventory schemes for seedlings in selected natural forests, Kenya, 2019

Forest type	Sampling Design	Plot size (m^2)	Sampling intensity (%)	Sampling effort		Sampling error (%)
				hrs/ha	ha/hr	
TRF	SRS	25	100	50.42	0.02	15.36
TRF	SRS	50	100	25.28	0.04	16.17
TRF	SRS	100	100	12.47	0.08	18.40
TRF	SSH (E-W)	50	5	26.00	0.04	22.51
TRF	SSH (E-W)	25	100	50.42	0.02	15.36
TRF	SSH (E-W)	50	100	25.28	0.04	16.17
TRF	SSH (E-W)	100	100	12.47	0.08	18.40
TRF	SSV (N-S)	25	30	50.89	0.02	20.92
TRF	SSV (N-S)	50	30	25.17	0.04	23.53
TRF	SSV (N-S)	25	100	50.42	0.02	15.36
TRF	SSV (N-S)	50	100	25.28	0.04	16.17
TRF	SSV (N-S)	100	100	12.47	0.08	18.40
MMF	SRS	25	100	40.68	0.02	14.74
MMF	SRS	50	100	20.10	0.05	15.62
MMF	SRS	100	100	9.98	0.10	18.22
MMF	SRS	400	100	2.43	0.41	24.04
MMF	SSH (E-W)	25	100	40.68	0.02	14.74
MMF	SSH (E-W)	50	100	20.10	0.05	15.62
MMF	SSH (E-W)	100	100	9.98	0.10	18.22
MMF	SSH (E-W)	400	100	2.43	0.41	24.04
MMF	SSV (N-S)	25	100	40.68	0.02	14.74
MMF	SSV (N-S)	50	100	20.10	0.05	15.62
MMF	SSV (N-S)	100	100	9.98	0.10	18.22
MMF	SSV (N-S)	400	100	2.43	0.41	24.04

Table 5 (continued)

Forest type	Sampling Design	Plot size (m^2)	Sampling intensity (%)	Sampling effort		Sampling error (%)
				hrs/ha	ha/hr	
DWF	SRS	400	10	1.17	0.86	-
DWF	SRS	25	20	21.75	0.05	24.40
DWF	SRS	50	20	11.00	0.09	21.42
DWF	SRS	25	30	21.83	0.05	18.39
DWF	SRS	50	30	11.11	0.09	20.62
DWF	SRS	100	30	5.72	0.17	21.18
DWF	SRS	25	100	22.38	0.04	9.87
DWF	SRS	50	100	11.35	0.09	10.67
DWF	SRS	100	100	5.65	0.18	12.12
DWF	SRS	400	100	1.45	0.69	18.64
DWF	SSH (E-W)	50	10	11.33	0.09	21.09
DWF	SSH (E-W)	25	20	22.17	0.05	21.31
DWF	SSH (E-W)	50	20	11.25	0.09	21.94
DWF	SSH (E-W)	25	30	22.00	0.05	18.76
DWF	SSH (E-W)	50	30	11.50	0.09	19.12
DWF	SSH (E-W)	25	100	22.38	0.04	9.87
DWF	SSH (E-W)	50	100	11.35	0.09	10.67
DWF	SSH (E-W)	100	100	5.65	0.18	12.12
DWF	SSH (E-W)	400	100	1.45	0.69	18.64
DWF	SSV (N-S)	25	20	22.00	0.05	22.82
DWF	SSV (N-S)	50	20	10.83	0.09	24.39
DWF	SSV (N-S)	25	30	21.89	0.05	17.97
DWF	SSV (N-S)	50	30	10.89	0.09	18.39
DWF	SSV (N-S)	100	30	5.44	0.18	19.76
DWF	SSV (N-S)	400	30	1.28	0.78	19.73
DWF	SSV (N-S)	25	100	22.38	0.04	9.87
DWF	SSV (N-S)	50	100	11.35	0.09	10.67
DWF	SSV (N-S)	100	100	5.65	0.18	12.12
DWF	SSV (N-S)	400	100	1.45	0.69	18.64

3.1.4 Relative efficiency of different sampling schemes based on cost, precision and accuracy: case of regeneration assessment

Figure 6 indicates that systematic counting of seedlings in 5mx5m-plot size with 30% intensity (SSV-5mx5m-30%) was the most efficient scheme in TRF with 83% efficiency; **SSH-5mx10m-5%** had 80% efficiency. In DWF, most efficient schemes were **SRS-10mx10m-30%** (91 % efficiency), **SSV-10mx10m-30%** (75 %) and **SSV-5mx10m- 30%** (74%). For MMF, all evaluated sampling schemes with intensity < 100% had efficiency <50%. Seedling surveys would be best carried out over 1-ha-plot, subdivided into 5mx5m sub-plots with 100%intensity.

4. CONCLUSION

This study demonstrated the practical aspect of screening simulated sampling schemes to develop reliable and cost-efficient inventory protocols in tropical forestry. It was possible to determine optimum plot sizes, sampling intensities and sampling designs that give the best balance between sampling error (as a measure of precision and/or accuracy) and sampling effort (as a measure of cost). Based on the attributes of the defined population of reference, it was possible to compute and illustrate relative efficiency of promising sampling schemes. Established efficient sampling schemes for tree regeneration were: SSH-5mx10m-5% for tropical rain forest, SSV/SSH-5mx5m-100% for moist montane forest and SSV-10mx10m / 5mx10m-30% for dry woodland forest in Kenya. Evaluation of possibilities to sub-sample one hectare area or not, applicable sampling schemes based on random or systematic sampling designs was achieved for the selected tropical natural forests with different levels of complexity, and using the most vulnerable stage of forest development (seedling stage). One-hectare-forest inventory method was found inevitable for regeneration assessment in montane forest where all evaluated sampling schemes with intensity <100% per hectare were not efficient enough (efficiency <50%) perhaps due to the slope factor. Same factor seems to influence sampling protocol for basal area than the complexity of forest ecosystem per se.

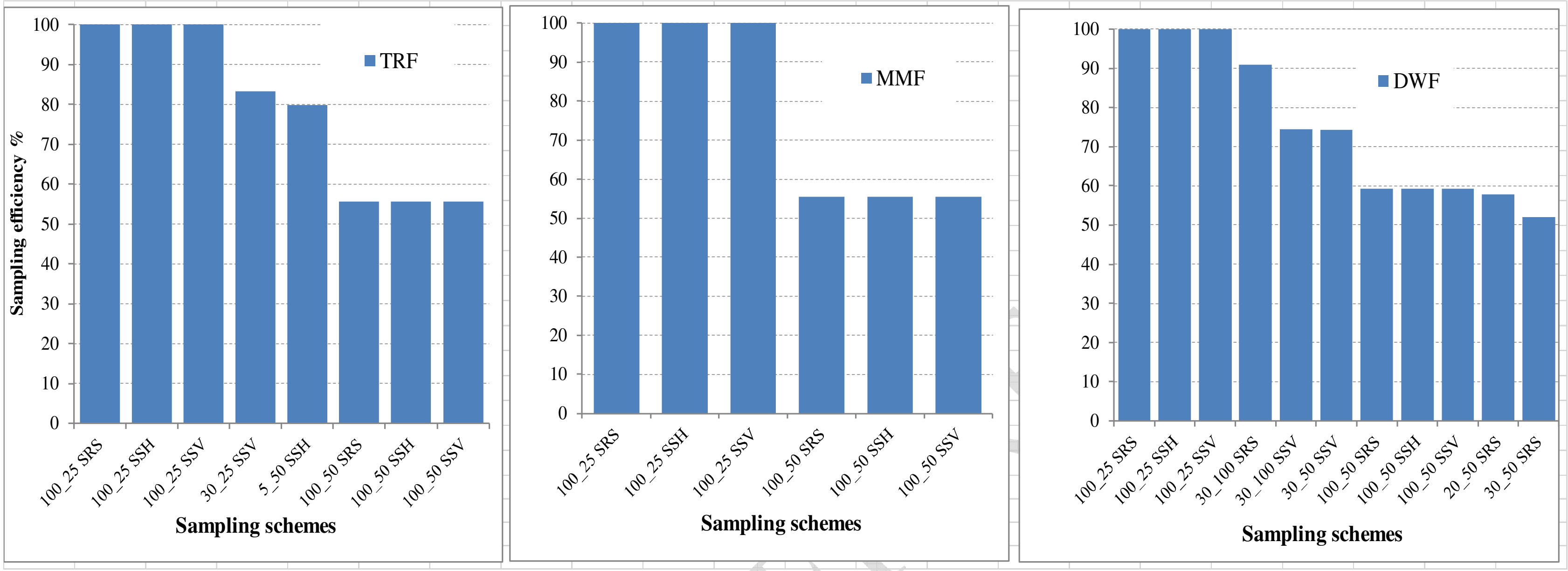


Figure 6: Relative efficiencies (cost, precision and accuracy combined) of candidate sampling schemes in assessing forest regeneration (no. seedlings ha^{-1}) in tropical rain forest (TRF), moist montane forest (MMF) and dry woodland forest (DWF), Kenya, 2019.

Key: SRS = Simple random sampling; SSH = Systematic plot sampling along horizontal transect; SSV = Systematic plot sampling along vertical transect; Sampling scheme e.g. "100_25_SRS" implies 100 % intensity, 25 m^2 plot size, SRS design

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