



Sampling Frame for the Vital Signs Global Monitoring System

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Acronyms and Abbreviations

AfSIS: Africa Soil Information Service

AVHRR: Advanced Very High Resolution Radiometer

ASTER: Advanced Spaceborne Thermal Emission and Reflection Radiometer

BIOTA: BIOdiversity Monitoring Transect Analysis

CCAFS: Climate Change, Agriculture and Food Security

CIESIN: Center for International Earth Science Information Network

CPC/FEWS: Climate Prediction Center/Famine Early Warning System

DEM: Digital Elevation Model

EBONE: European Biodiversity Observation Network

FAPAR: Fraction of Absorbed Photosynthetically Active Radiation

GBIF: Global Biodiversity Information Facility

LCCS: Land Cover Classification System

LDSF: Land Degradation Surveillance Framework

LSMS: Living Standards Measurement Study

MISR: Multi-angle Imaging SpectroRadiometer

MODIS: Moderate Resolution Imaging Spectroradiometer

NCEP: National Centers for Environmental Prediction

SRTM: Shuttle Radar Topography Mission

TAMSAT: Tropical Applications of Meteorology using SATellite data and ground-based observations

TARCAT: TAMSAT African Rainfall Climatology And Time-series

TEAM: Tropical Ecology Assessment and Monitoring

VIIRS: Visible Infrared Imager Radiometer Suite

Definitions

Landscape: a 10 km x 10 km area for which high-resolution (<1 m GSD) satellite images are repeatedly acquired on a daily to five-year interval (=‘Tier 4 sample’ [Vital Signs], and similar to a ‘sentinel landscape’ [AfsIS, CGIAR]).

Patch: an area of any size and shape with geographically-defined boundaries (i.e. a spatially-explicit polygon) which is considered to be homogeneous, at the scale of interest, with respect to land cover and use (=habitat [biodiversity]; =field [agronomy]; =stand [forestry]).

Feature: the finest elements identifiable on high-resolution images (=object in eCognition), typically 1-5 m in scale. Examples include individual tree canopies, dwellings, roads, hedges, river reaches etc.

Plot: an area over which a sample is taken, with known location and dimensions (in Vital Signs, typically on the order of 100 m x 100 m (1 ha)). Photo-plots, rapid roadside plots, and calibration/validation plots sampled from high-resolution images without an *in situ* visit are special cases of the general plot concept. Cultivated area plots in the Tier 4 landscapes, referred to elsewhere in this document as ‘fields,’ are another special case, where the extent is defined by the boundaries of the cultivated patch.

Sub-plot: an area nested within a plot for purposes of efficient and replicated sub-sampling. For instance, AfsIS uses 4 subplots 12.2 m apart in a Y-shape, each with a radius of 5.6. Vital Signs generally uses an E-shaped sample of 36 subplots of variable diameter (2-5 m radius) arranged on a 20 m grid.

Quadrat: a portable, known-area physical frame less than 1 m² in area (typically 0.5 m x 0.5 m, but other sizes and shapes are possible). Used for sampling field crops, the herbaceous layer in semi-natural areas, and the litter layer and soil surface condition.

Point: a geographical location with a dimension of <1 m² at which an observation is made. Points have the attributes of latitude, longitude, height/depth above or below a datum (nominally the ground surface or water surface), date and time, and one or more observation variables associated with the point.

Enumeration Area: a census district, typically containing a thousand or more households. A list of households in the enumeration area provides the frame from which a subsample is drawn for the household panel survey. The household results are agglomerated up to the enumeration area using census statistics before being combined at regional level.

Household: a small group of people, typically closely related, living together as a functional unit and sharing resources.

Community: a group of households sharing a landscape and its resources, interacting socially and economically and usually in the same administrative area (=village).

Station: point location with continuous, automated recording of one or a few key variables (examples are a river flow measurement station, a weather station or a camera trap).

Executive Summary

Vital Signs (VS) is a monitoring system that implements a broadly common approach to monitoring linked changes in human well-being, agricultural and ecosystem services outcomes. The initial phase, funded by the Bill and Melinda Gates Foundation, is being implemented in three large regions of Tanzania, Ethiopia and Ghana. It is hoped that the experience gained in these countries will lead to the system being adopted more broadly in Africa and the world.

The Sampling Frame broadly defines the statistical approach that guides where, when and how observations are made, and how they are analyzed in order to generate reliable estimates, along with quantified uncertainty, for the study region as a whole. The Sampling Frame is supplemented, in separate documents, by detailed methodologies describing precisely how each observation variable is defined and collected, as well as by workflows tracing how variables are transformed, combined, analyzed and reported as indicators and indices.

The VS system uses, where appropriate, data from other observation, monitoring and census systems, which have their own sampling frames. VS uses three frames for different purposes. An *area-based* frame is used for ecosystem and agricultural landscape attributes which have a definable areal extent. This frame mostly uses land cover classes, mapped at ~300 m resolution over the whole region, as the basis for sample distribution and statistical extrapolation of the sample. A *panel-based* frame is used to guide household surveys, mostly pertaining to human wellbeing variables and information relating to use of the land and its resources. A *flow-based* frame is used to sample and extrapolate water-related variables.

The optimal combination of coverage and detail is obtained by organizing the sampling into four *Tiers*. Tier 1 covers the entire extent of the region ('wall-to-wall') with relatively coarse resolution remotely sensed or modeled data. Tier 2 consists of several hundred or thousand locations, where information is periodically collected in plots of around 1 ha extent. Tier 3 consists of a small number of points where continuous data is recorded using automated sensors. Tier 4 consists of a small number of 10 x 10 km *landscapes* where very detailed, highly-resolved and spatially-linked information is collected.

Overview: How the Frames Fit into an Observing System

The Vital Signs monitoring system is a prototype integrated monitoring system for agriculture, ecosystem services and human well-being. It is specifically designed for use in rapidly expanding and intensifying agricultural landscapes, initially in Africa. It is implemented in *regions*, which are contiguous areas of about 250,000 km². These are usually at a sub-national scale, typically areas targeted by governments or the private sector for agricultural development. A region is characterized by broadly uniform socio-ecological conditions (or a small number of repeating sets of conditions), each with some range of internal variation. Each VS region has its own detailed sampling design that specifies the sampling units and details of the sample number and its spatial distribution. But the same general principles (embodied in this sample frame document) are followed in all VS regions, allowing comparisons across regions. The Vital Signs sample frame is based on experience gained in TEAM (see acronym list), AfsIS (which draws on LDSF, both covered in Vågen et al. 2010) and LSMS. It is designed to be broadly compatible with these schemes while flexible enough to fit in with other programs, including future schemes that can currently only be guessed at.

For data collected directly by Vital Signs, standard methods are used to the greatest extent feasible. In some cases a single method will be specified, in others a restricted range of well-documented methods will be permitted. For data integrated from collaborating monitoring activities, Vital Signs primarily specifies the variable to be observed, and requires that the reported value be accompanied by a robust estimate of accuracy and a documented method. Throughout the Vital Signs system, the accuracy specification (and thus the sample intensity) is based on *utility* ('fitness for use'; in other words, is the accuracy sufficient for the use to which the data are being put? Would more accuracy lead to a different decision by the user?). In the prototyping phase of Vital Signs, we are more interested in *characterizing* the uncertainty and quantifying the sample effort required to attain various levels of accuracy and statistical power to detect change than in achieving an *a priori*-defined level of accuracy. Our first phase objective is to determine what the utility level is in various contexts, and what it would cost to deliver an observation system that satisfies that level. This inverts the usual logic for sampling frame design, which assumes that both the variance and the desired accuracy are already known.

The design of the VS sampling frame follows the principles and terminology of de Gruijter et al. 2006. In their terms, it is a compound, hybrid system (i.e. using a variety of different sampling frames and statistical approaches). This is inevitable because the system covers many variables, and one optimized approach cannot be developed; it also covers a range of scales, which means that different sampling frames apply at different levels. There are thus elements of random, model-based designs and systematic grid designs. This document mostly deals with the sampling frame, which is just one element of the monitoring system. Detailed data collection protocols and analysis workflows are in separate documents, referenced here.

Table 1: A summary of the various sample unit types used in Vital Signs.

Sample unit name	Scale	Number per region	Notes
Region	~250 000 km ²	1	An area defined by a key stakeholder, or in some cases, a jurisdictional boundary
Land cover type	Each at least 1% of region and no more than 20%	10-20	LCCS level 2 or 3
Landscape	10 x 10 km	~5-10	Repeated high-resolution imagery
Patch	Any size, but typically 10-1000 ha	Thousands	Contiguous mapped land cover/use units
Plot	~1 ha (100 m x 100 m)	~500 detailed plots	Revisited every 3-5 years
		~5000 rapid plots	Not necessarily revisited
Subplots	Variable, ~ 10 m ²	9-36 per detailed plot	E-sampling suggested as the way to distribute within plots
Quadrats	~0.25 m ²	9-36 per detailed plot	
Points	No dimension	Variable	

The Principle of Hierarchical, Sparse and Partially-Nested Sampling

A *hierarchical* sampling scheme is one where information is gathered at more than one spatial and/or temporal resolution, and agglomerated or disaggregated to a range of spatial or temporal scales. *Sparse* means that only a small fraction of the total area of a unit is actually observed. *Nested* means that the information at the finer scale is geographically encompassed by the unit at the larger scale; *Partially-nested* means that some (but not all) samples follow the strict hierarchical principle. For instance, there can be several hierarchies operating in parallel, or some finer-resolution samples may be outside the geographical footprint of the higher-scale unit, or some information may be derived from other, non-hierarchical sources.

The hierarchical principle in Vital Signs is conveyed by the notion of *Tiers*. As the tier number increases from 1 to 4, so the fraction of the landscape physically sampled decreases, but the effort per unit sample increases (Table 2).

In Vital Signs there are three basic types of sampling frame: area-based, panel-based and flow-based. The area-based frames apply to natural ecosystems (including aquatic ecosystems) and agricultural landscapes. The panel-based frame applies to households. The flow-based frame applies to water quantity and quality and in some circumstances to the demand side of ecosystem services (i.e. we would require more effort for services consumed in greater quantities).

Table 2: Summary of the hierarchical sampling strategy in Vital Signs for an area of 250 000 km². Guideline sample numbers will scale somewhat with the total area of the region, but not strictly proportionately – more heterogeneous landscapes need more. The numbers given here are tentative, and will be refined in regional sampling designs.

Tier	Terrestrial natural and semi-natural ecosystems	Transformed agricultural landscapes	Freshwater ecosystems	Human wellbeing
1: simple measures, complete regional coverage at moderate resolution, based on models and remote sensing	Land cover map to LCCS level 2, repeated at 3-5 year intervals at 500 m resolution			Population distribution at 1 km resolution
	Vegetation type Tree cover Tree height Estimated biomass Start and end of green cover 10-day FAPAR Modeled NPP	Crop type, as delineated in Table 3 Bare soil fraction Tree cover Planting date and harvest date duration 10-day FAPAR Modeled yield Drought index	Drainage map from SRTM DEM River reach classification 10-daily rainfall at 5 km resolution 10-daily PET at 5 km resolution Modeled 10-day river flow	Disaggregated Gross Regional Product from national statistics Disaggregated agricultural productivity and livestock, income, and health from national statistics
2: Periodically revisited plots, 1 ha resolution, in situ detail, and households. A statistically valid sample	500 1 ha plots, revisited 3-5 year intervals	250 1 ha plots, revisited 2-year intervals	25 river health reaches, revisited annually 12 water quality locations sampled monthly	500+households, revisited at 1-3 year intervals dependent of national survey panels
	3000-5000 rapid assessment plots, revisited at 3-5 year intervals	1000 field inspections for crop types, pests and weeds	200 riparian rapid plots for weeds and visual flow and quality	
3: Continuous automated stations	VS weather stations up to 4			
	In some locations at some times, camera trap grids	Farmer calendars	~6 gauged flow stations	
4: Process-oriented studies at high resolution	5-10 10 km x 10 km landscapes, with high resolution (<1 m) classified imagery every 3-5 years, each with 30+ included households and associated agricultural fields and known resource areas, communities/markets, some level 2 agricultural and natural plots and 4 gauged micro-watersheds			

Sample Location Schemes: Purposive and Random

The notion of *purposive sampling* (i.e. non-random in the strict statistical sense) is applied in VS when (because of cost constraints) the total sample size is small (<5), or when samples intrinsically cannot be randomized due to the physical attributes of the sample technology and/or environment to be sampled. The location of purposive samples is based on expert decision guided by a set of

criteria: the sample location is subjectively determined in order to satisfy a particular project objective. For example, the location of the VS 10 x 10 km landscapes is purposive: they are placed where change is anticipated and gradients of use intensity are represented.

Stratified samples are the approach of choice where it is possible to *a priori* classify the area or population to be sampled into a number of strata which have the property that the variation within the class of particular attributes of interest is less than the variation within the region or population as a whole. Stratification allows the estimation accuracy of class-average values to be maximized with a reduced amount of total sample effort. The number of samples per stratum is adjusted depending on (1) the user-required accuracy for that cover type, (2) the internal variation in the type, and (3) the total area covered by the type. Generally, the number per stratum would be not less than 30. Plot samples within a landscape are placed on a stratified random basis; plot samples outside of landscapes are placed on a stratified cluster-random basis due to the constraint of difficult access in many areas.

Wherever practicable, the samples within a stratum are randomly located in order to eliminate observer bias. In most cases the same sample locations are revisited in time, since this increases the power of change detection relative to drawing a new sample from the population in every case. Randomization is applied initially, or when new samples need to be added to the set. In practice, some compromise is often needed because true randomized locations at all scales are not reachable with reasonable effort. Methods which approximate true randomization are generally used in Vital Signs: for instance, by applying a systematic grid over what is assumed to be background random variation (e.g. subplots and quadrats within plots); sampling at random distances along a road (with a random distance from the road, not exceeding a reasonable travel cost); or by allowing substitution of a randomly-drawn sample with another randomly-drawn sample if the first is inaccessible (plots).

Area-Based Sampling Frames

The sampling frame for area-based samples is determined by the moderate-resolution (250-500 m) regional land cover map, derived from remotely-sensed data at the beginning of the observation period (Globcover 2009 is the default), and then repeated at least once every 5 years. (Note that the remote sensing imagery used for this purpose is repeated daily to 10-daily, and, allowing for cloud cover, has an approximately monthly temporal resolution. The composites built from these multi-temporal observations permit wall-to-wall cover often not achievable using higher resolution imagery, and allow phenology to be used as one of the classifiers). In Vital Signs terminology, this is a *Tier 1* sample. The entire region needs to be Tier 1 remapped at least at 5-year intervals, but sub-regions where rapid change is known to be occurring may be remapped more frequently (for instance annually), and may use higher-resolution imagery if desired (e.g. low-cost Landsat-class images with a resolution of about 30 m). In this case, the latest merge of the moderate and finer resolution mapping is the one that is operative as the frame at any given time.

Tier 2 and 3 sampling is stratified according to the different land cover classes obtained through the Tier 1 classification; in the case of transformed areas (i.e. those areas not classified as natural or

semi-natural) they are further stratified according to an index of agricultural intensification (detailed in the agricultural section of this document). The Tier 2a detailed plot sampling intensity is approximately 1 per 500 km² (i.e. 100-500 plots), while the Tier 2b rapid, semi-quantitative plots have an intensity of 1 per 50 km². The purpose of the Tier 2b sample is to validate the accuracy of the Tier 1 land cover map on which the sample frame is based; for statistical reasons this needs a sample size of several thousand. The tier 2b plots in inaccessible and remote areas will make use of areal photos and high-resolution images to ensure unbiased coverage. Tier 3 consists of whatever climate recording stations already exist, supplemented with a few from VS. They are aerially extrapolated using sophisticated data fusion techniques involving elevation, regional trends and remotely-sensed covariates such as cloud temperature: the DayMet method is an example. Tier 4 consists of complete mapping at 1 m resolution of 5-10 10 km x 10 km *landscapes*; its purpose is to enrich the land cover mapping of transformed areas with detail (such as individual fields and inter-field habitats) not visible at the ~500 m resolution of the land cover map, but only for a small number of cases, in order to understand the operative processes.

The Basis of Spatial Statistical Agglomeration for Reporting Purposes

It is not proposed that the regional means of given variables be determined from the simple averaging of the individual plot-level observations, but by an area-weighted average. By stratifying and allocating samples in rough proportion to the area occupied by each class the power of the overall system is preserved. It is recognized, however, that the proportionality will only be approximate, and will vary over time. It is proposed that for any reporting polygon X with area A_X (which could be any scale up to the entire region), the reported value of variable v in polygon X will be

$$V_X = (\sum_L A_{X,L} * v_L) / A_X$$

Where v_L is the mean value of V inside land cover type L, measured over the entire region. The latter assumption can be relaxed if the number of samples in land cover L (n_L) is sufficiently high that the subset n_{X,L} is sufficiently large to provide a good estimate. The confidence interval for V_X (assuming approximately normal distributions) will be

$$\pm z_{\alpha} * \text{sqrt} (\sum_L (A_{X,L} / A_X) * \sigma_L^2 / n_L)$$

Landscape Sample Frame and Selection Rules

The purpose of the Tier 4 landscapes is twofold: to monitor changes in land cover at a fine-scale over time, and to provide a more detailed understanding of the spatio-temporal relationships among agricultural management practices, ecosystem services and human well-being. As a guideline, 5-10 10 x 10 m landscapes will be located in each region. There are fewer Tier 4 landscapes than there are Tier 1 strata, therefore this is only a partially-nested system, and Tier 4 landscapes are not directly

extrapolated to the region. The Tier 4 landscapes are located based on a set of criteria and the judgment of regional experts. The general principles are:

1. The overwhelming majority (75%, ~8) of the landscapes are placed in areas that are currently undergoing transformation or that have already undergone agricultural transformation. In landscapes where there is a clear intensification gradient radiating from a road or settlement focal point, the landscape could be positioned so as to capture this gradient: for instance by placing the settlement towards one side or corner of the square. Alternately, one side or corner could be anchored in a protected area that is unlikely to transform, but which has contrasting areas outside of it. The result will be a gradient of intensification across the image. If necessary, two or more images can be located adjacent to one another to capture the full extent of this gradient. In landscapes where the settlement pattern is diffuse, the exact location is less critical. Where possible, there should be an area of the less-transformed types somewhere in the image to act as a contrast. The images representing landscapes should be distributed across the region to represent the main socio-ecological settings; they are deliberately located to be a purposive sample, but allow for a very detailed spatio-temporal analysis of small-scale patterns and processes within each landscape. Sampling *within* tier 4 landscapes is typically stratified random.
2. The remainder of the landscapes (~2) may be used to ensure that there is adequate coverage of areas of special interest, such as micro-watersheds that have been selected for the river sampling (especially those undergoing land cover transformation; the control watersheds may be adequately covered by the moderate resolution images).
3. The aim is to have 30+ household surveys associated with each landscape (i.e. the dwellings, fields, and most of the resource-collection areas of the sampled households should be within the landscape). The list-based frame for household panel surveys will be used. If there is a comprehensive and recent list of households in the area from administrative records or previous surveys, a random sample of households will be selected from that list. In cases where such lists do not exist, the list must be generated, for instance by mapping out all households discernible on the high-resolution image, with help of local people. If some chosen households decline to participate or are unreachable, a supplementary sample will be drawn from the list.

Natural and Semi-Natural Ecosystems

This sampling frame applies to the areas classified as natural and semi-natural (both terrestrial and aquatic) in the Tier 1 land cover map. It includes natural (i.e. not plantation) forests, woodlands, savannas, bushlands, shrublands, grasslands, deserts and wetlands (other than paddy rice fields). It includes areas of grazing land that are not intensively managed (i.e. naturally-recruiting plant species, not irrigated or fertilized). It includes harvested natural forests and woodlands (including recent clearcuts and areas re-growing from forestry or recovering from slash and burn agriculture). It includes large water impoundments, and protected areas such as national parks, forest reserves etc.

Table 3: Vital Signs Tier 1 land cover classes in Land Cover Classification System (LCCS) terms.

LCCS level 1 land-cover classes (=Africover Classes)	LCCS level 2 classes - enriched with information on tree canopy cover and height, seasonality	LCCS level 3 – enriched with dominant species information mainly from vegetation maps
Terrestrial natural/semi-natural	Forest (>70% canopy cover, >2 m)	Type of forest
	Woodland (40-65%, >2 m)	Type of woodland
	Savanna (10-65%, >2 m)	Type of savanna
	Shrubland (10-60% cover, < 2 m ht)	Type of shrubland
	Grassland (0-10%)	Type of
Terrestrial cultivated	Short-duration crops	Crop species/mixture/rotation
	Mixed tree-short duration crop systems	Dominant trees, crop species
	Plantations and orchards	Species
Aquatic/regularly flooded natural/semi-natural	Marshland (including saline marshes)	Type (permanent, seasonal, saline, estuarine), species
	Riparian or mangrove forest	Type and dominant species
Aquatic/regularly flooded cultivated	Rice paddies	
	Aquaculture	
	Floodplain farming	
Deep open inland water (natural or artificial)	Lakes	Shallow (=pans)
		Deep (thermocline present)
		Saline
	Impoundments	
Bare (rock, sand-dune, salt pan)	Rock or gravel	
	Sand	
	Saline	
Artificial covers	Roof	
	Paved/sealed	
	Road	

Tier 1: Map of Ecosystem Types for the Region

The Tier 1 level 2 LCCS classification for natural and semi-natural ecosystems (largely based on vegetation gross structure and capable of automated classification using remotely sensed data alone) will be enriched to a level 3 classification (i.e. including additional information about dominant species and geomorphology). This will be done initially by overlaying the land cover classes with the best-available national-scale vegetation map, simplified where necessary in order not to have too many partly overlapping classes, and a terrain classification derived from a 30 m Digital Terrain Model and the best available geology map.

In later phases, the vegetation map will be iteratively improved using the Vital Signs Tier 2 and 4 data. In all cases, the level 3 classification is viewed as being ‘on balance of probability’ rather than definitive, since it is based on a model (a vegetation map is someone’s mental model) rather than pixel-by-pixel observation. The result will be a spatially complete map of polygons of consistent

ecological conditions, which will form the basis for sample stratification for natural and semi-natural covers. Where appropriate, this may be a post-stratification; for instance, where the cover class has changed but the sample location is fixed, or where the sample variation within a strata can be associated with more detailed information that was used in the initial stratification.

Tier 2a: Detailed Plots

The detailed attributes of the natural and semi-natural land cover type are determined in plots of 1 ha each. The plots are revisited at an interval of 3 to 5 years. For this reason they must be precisely geo-located, but preferably not permanently marked. One corner of the plot (the *origin*) must be geo-located to within a 1 m resolution (a good-quality non-differential GPS averaged over 5 minutes will provide this accuracy; new-generation GPS technologies will do so routinely), and with 5 m accuracy (a single GPS single record) at each of the other 3 corners, plus a compass-direction orientation of the first leg of the sample grid (e.g. 23 degrees magnetic).

The sample design is random, with exclusion of unreachable locations. The plot location will be determined *a priori* by overlaying a polygon of reachable areas (a buffer of 1 km around all roads and tracks which are passable by a 4-wheel drive vehicle for some part of the year) on the regional land cover map. Next, n random points per land cover type will be selected, where the initial n is roughly $(0.8 * N * \text{fraction of region covered by the land cover class})$ and N is the total number of 2a plots), then adjusted marginally to ensure that no land cover class has so few points (<10) that robust estimation of the mean is compromised, nor too many points (>20% of the total across all classes), in which case the land cover class should probably be sub-divided.

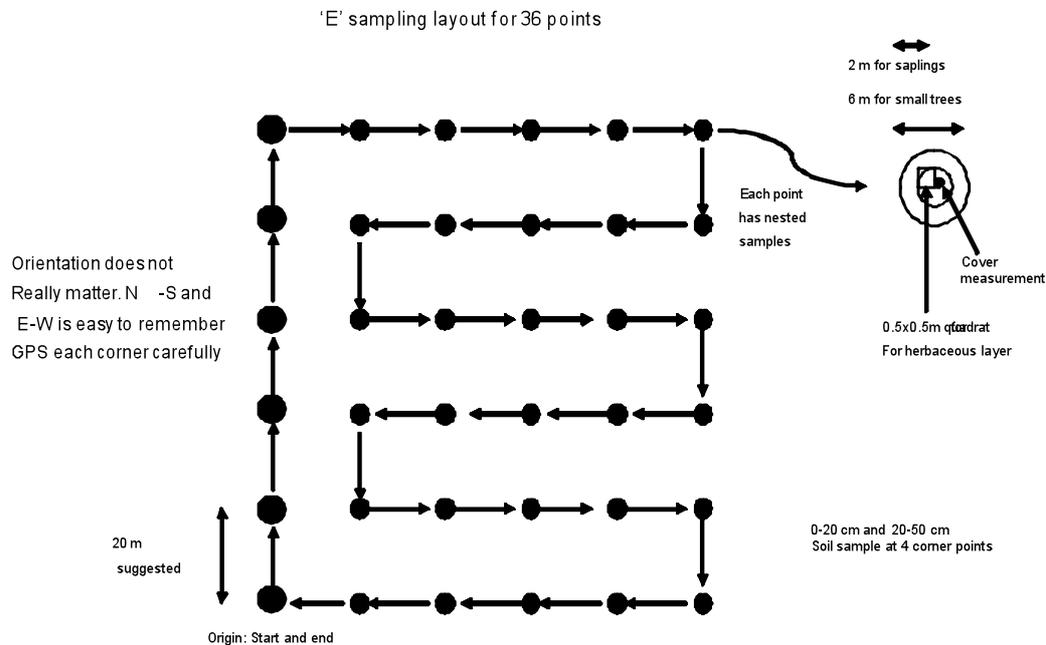
In subsequent iterations, once the standard deviation (σ) of the attributes of interest within the class are known, and the user-defined accuracy (+ a) is known, the sample sizes per land cover class can be optimized by a rule such as

$$a=2 * \sigma/\text{sqrt}(n), \text{ i.e. } n = (2\sigma/a)^2$$

which assumes that the variable is approximately normally distributed and that a has been defined as the absolute range of permissible uncertainty, with about 95% confidence. Note that none of these assumptions can be taken for granted.

About 20% of the plots (~100, or 10 per landscape) are designated to be within the 10 km x 10 km Tier 4 sample areas defined as *landscapes*. Within these landscapes they will be randomly placed per stratum, based on the fine-resolution land cover mapping of the landscape.

Figure 1: E-sampling subplot layout. This is a systematic grid sample. There is nothing magic about the E shape, it is simply the most time-efficient way to sample a large, approximately-square regular grid. For simplicity, the orientation is N-S and E-W and the dimensions are fixed, at 20 meter grid intervals.



For grassland, shrubland, savanna and woodland land covers, it is recommended that the subplots in a plot be distributed using the E-sampling protocol. The standard E consists of a regular grid of 36 subplots, spaced 20 m apart, in 6 rows each containing 6 circular subplots (figure 1). The 'E' covers an area of 100 x 100 m. While the actual dimensions are not very sensitive (except that the circular subplots must not overlap, and should preferably be clearly separated by about one diameter), they are standardized to keep things simple. The Vital Signs dimensions (100 m x 100 m) are selected to appropriate the pixel size of the moderate-resolution Tier 1 remote sensing on which the whole system stratification is based. The 1 ha overall dimension should be kept to unless there is good reason not to; for instance, the shape can be altered to a long narrow rectangle for sampling linear patches such as a riparian forest, while keeping the 1 ha area.

It is not important that the entire hectare be in one land cover type – it is a sample of the landscape average within a broad cover type, which may contain fine-scale incursions of other cover types, and this pattern may change over time. Judgment may be applied on subsequent re-sampling if the sample plot is now an outlier (for instance, if a building or road was constructed on part of the plot). It may then be necessary to close the plot and relocate it either to an unaffected area of the former land cover, or within the new cover type – whichever is relatively under-sampled. If the land cover change is ongoing, it is better to keep the plot location stable, allowing the change to 'wash over' it and accepting that it will be a mixed-cover plot.

The raw observations per plot (in addition to the date, location and orientation) are the stem circumference and height profiles by species for woody plants (trees and shrubs), from which biomass is derived by allometry, the canopy cover, and the biomass by species in the herbaceous layer. In addition, quantitative data regarding the state of the soil surface are collected within the same quadrats used for the herbaceous layer. Soils will be sampled at 0-20 cm and 20-50 cm from the four corners of the plot unless an impediment in the profile is reached. The soil samples will be treated and analyzed according to the AfSIS protocol, which also calls for some *in situ* analyses such as finger tests for texture. The minimum set of data for soils includes particle size distribution, pH, exchangeable macronutrients (Ca, Mg, K, P), bulk density, and %C.

In the E-sampling protocol, the systematically located subplots in which the observations are made are circular, with a radius that can vary between plots (see table 4) but is fixed for all subplots within a plot. The objective is to sample about 100 individuals of each target class, i.e. 3 per subplot on average. For example, if you are recording all trees taller than 2 m in height, and a visual inspection suggests that there are about 400 such individuals per hectare (10,000/mean inter-tree distance, 2 gives a rough estimate of density per hectare), then 36 plots of 5 m radius should capture on average 113 individuals, if they are randomly distributed. By contrast, in a shrubland with a shrub every 2 m, a radius of about 2 m is about right. In a plot with mixed life forms (e.g. a sparse canopy layer and a dense sapling or shrub layer), two radii can be used at each subplot sample point: a larger one for the sparse trees and a smaller one for the dense shrubs.

Table 4: Guideline for adjusting circular subplot radius for different vegetation types.

Description	Individual density	Guideline plot radius (m)
Grassland with occasional trees	100	10 m (you should increase inter-subplot distance to at least 3 r)
Very open savannas	200	7 m
Typical savannas, tall woodland, forest	500	4 m
Typical bushland with about 40% cover	1000	3 m
Dense bushland/thicket	2000	2 m
Row-crop planting, dense tree seedlings	10,000	1 -3 m

Other approaches to Tier 2-type plot data collection in use by partner organizations may, in principle, be acceptable where there are compelling reasons to adopt them rather than the E-sampling protocol, provided that the sample frame applied provides unbiased estimates of the same variables, with error ranges and a documented method. Examples are the TEAM method for complete stem inventory in 1 ha forest plots, and the AfSIS/LDSF method of an area about 1 km² containing a cluster of 10 randomized plots each with 4 subplots, where the T-square method is used to collect the tree data.

Tier 2b: Rapid Semi-Quantitative Plots

The purpose of the rapid plots is to provide a validation and calibration data set for the semi-automated Tier 1 land cover map generated from remote sensing. The Tier 2b sample is principally used for determining the accuracy of the Tier 1 classification, using the kappa statistic (Congalton &

Green 1999). Since Tier 2b is a numerically large sample, a portion can be used for calibration (to refine the classification through training) while the remainder is reserved for validation. The sample consists of ~2000-5000 points, randomly located and post-stratified using the Tier 1 land cover map. The information for the majority of these will be extracted from the desktop examination of high-resolution images (for instance from Google Earth). In addition, a set of *in situ* 'rapid plots' may be used for collecting a large sample of quickly observed information, which is not apparent from remotely sensed data. Examples are the crop type planted, the species dominance of natural vegetation, land use and soil surface conditions, the presence of weeds and whether rivers are flowing, dry or stagnant. Rapid *in situ* plots can be randomly located in landscapes, but outside of landscapes they will be confined to the vicinity of roads and tracks. The latter therefore do not comprise a random sample, and should be used for calibration only.

The core information collected at each rapid plot (which should take less than 5 minutes) is a date (the date of the imagery, when using remote sensing), a location within 5 m and the information needed to reach a level-3 LCCS class: (1) evidence of regular flooding, (2) a visual assessment of the height and cover of the tree (or shrub) layer, and (3) the dominant plant functional class (crop, tree, grass).

In addition, for *in situ* rapid plots an extended species list of trees and herbs (including sub-dominant species, but not intending to be an exhaustive survey – all those contributing at least 5% to the cover), visual clues to land use (e.g. grazing, tree cutting, protected) and land condition (e.g. erosion) are noted. The *in situ* observation is substantiated with a panoramic, date-stamped, GPS-coded digital photograph taken according to a standardized procedure.

Tier 3: Continuously-Recording Stations

No specific area-based Tier 3 stations are proposed for natural and semi-natural areas in Vital Signs, though research collaborators may add some on their own budgets to take advantage of the extrapolation frame offered by VS. An example of a Tier 3 station in a natural landscape is an eddy-covariance flux tower for measuring carbon exchange, or a network of sound recorders for recording animal vocalisations. Supplemental weather stations may be necessary in some VS regions; they serve both the transformed and transformed landscapes. Multi-sensor automated weather stations are required in order to provide all the inputs necessary for making water balance calculations: precipitation, air temperature, relative humidity, wind velocity (wind direction is usually included as well) and solar radiation. In reality, many of these observed variables can be substituted with remotely sensed, modelled or interpolated proxies, so the role of weather stations in VS is primarily to act as calibration and validation for the inferential models. Tier 3 hydrological recording stations are described below, under the flow-based sampling.

Tier 4: Treatment of Natural and Semi-Natural Areas

Natural and semi-natural areas in the context of the Tier 4 10 x 10 km landscapes consist of both large blocks of uncultivated or un-built land within the landscape (several hectares in extent, and therefore visible and mapped in Tier 1 moderate resolution land cover map), as well as much smaller semi-natural features within what is mapped at the Tier 1 resolution as a transformed landscape (for

example, inter-field areas, small woodlots and livestock pens, abandoned or fallow fields, riparian zones, hedges and road margins). These will be classified at fine scale (<5 m) using eCognition applied to high-resolution images and the EBONE habitat classification scheme.

Transformed landscapes

This includes areas predominantly devoted to crop agriculture, integrated livestock systems, planted pasture-based livestock, agroforestry, plantations and orchards, including the small-scale inclusions (<500 m dimension) of natural or semi-natural cover and human settlement within them.

Tier 1: Mapped Coverage

Tier 1 for transformed landscapes is exactly the same as for untransformed landscapes: a moderate resolution, remotely sensed complete mapping of land cover type, which then forms the basis for area-based extrapolation. The LCCS level 3 classification in this case should include sufficient information to distinguish not only crop type (or rotation type) but also cropping intensity (e.g. large-scale commercial, high-input cropping from small-scale, subsistence, low-input cropping).

Tier 2: Detailed Plots

Within the Tier 1 agriculture land cover classes, the 1-hectare grid ('E-sample') sample frame will be applied in the same general way as it is in the natural and semi-natural (untransformed) land cover classes, and subject to the same location rules (an approximately area-proportional stratified random sample, constrained by an accessibility condition). Within the 1 hectare plot, similar measurements will be made as described for natural and semi-natural systems, as applicable: if trees are present, they will be recorded with the circular subplot protocol; if herbaceous plants (including crops) are present, they will be sampled with quadrats; and the soil condition and sampling is essentially the same.

Additional information that can be directly observed in the field will be obtained at the sub-plot level on crop types/varieties (including annual crops, trees, weeds) and management practices that can be directly observed in the field, including tillage practices (till/no-till, mechanization), soil conservation structures (rock walls, biological strips, trash lines), water management structures and equipment. Since many of the agricultural variables such as yields and inputs are seasonally dependent, it is not likely that these can be measured in the field consistently. These details on inputs, outputs and management will be obtained in the Tier 4 landscapes as part of sampling of agricultural fields and linked with household surveys (see below) and with ecosystem services.

In order to investigate links between environmental parameters, agricultural production and livelihoods, a fraction of the Tier 2 detailed plots will be located within the Tier 4 landscapes – 5 to 10 per landscape.

Tier 3: Continuous Records

Permanent agricultural trial plots operated by National Agricultural Research agencies are an example of a Tier 3 agricultural sample. No specific allowance is made in VS for Tier 3 samples in agricultural landscapes, but many of the Tier 3 national weather stations will be located in such landscapes.

Tier 4: Agricultural Landscapes

The purposes of the Tier 4 landscapes are 1) to quantify the value of ecosystem services (including agricultural products) for households; 2) provide system-level, integrated measurements of the causal processes underlying observed changes in ecosystem services and human well-being as they relate to agricultural intensification and management; 3) measure and track sustainability, through changes in inclusive wealth or related measures; and 4) establish the spatially-explicit links between resource areas, resource use, fields, living areas and household wellbeing. The system-level, Tier 4 data also are essential to support the analysis of trade-offs and synergies among agricultural production and other ES and HWB outcomes.

In this case the sample frame is list-based, following the procedure used for randomly selecting households within the Tier 4 landscapes (described earlier). In addition to the household surveys that are administered to these households (see following section), the households will be asked to identify their fields on the high-resolution image, and those patches within the 10 x 10 km landscape from which they derive other resources. Additional information will be collected for these fields and resource management areas.

For each of those focal households, the boundaries of all agricultural fields (including annual crops, agroforestry and fallows, tree plantations and pastures) will be digitized and geo-referenced. The information collected for the fields associated with these households will include planting dates, plant density, nutrient inputs (types and amounts), crop types and varieties (including trees), date of flowering, occurrence of pests and diseases, soil management practices (e.g. frequency and method of cultivation), water management, and others to be determined to indicate the degree of agricultural intensification. The households will also be asked about the number and type of livestock they own and whether it was bought, sold, consumed, died or was born in the survey period.

Focal households will also be asked about the major fuels used for lighting and cooking, how many hours spent collecting fuelwood and the key locations where fuelwood is harvested; sources of water for drinking and household use, water treatment, methods for obtaining water, and time spent collecting water; sources of building materials (e.g., thatch for roofs); wild meat, wild fish and insect consumption; as well as medicinal plant harvest and honey cultivation or wild harvest. This information will be solicited from the farmer during the household interview. It can be verified by field visits and visual inspection. These fields will be re-sampled on 3-5 year intervals to track changes related to agricultural use and intensity.

Surface soil samples will be taken (0-20 cm depth) from each of the fields. Key soil variables will be measured, as far as possible, in the field (i.e. not requiring samples to be sent to a laboratory, but using visual assessment techniques for soil loss, color and surface state, finger tests for texture and field lab tests for pH, salinity, nitrates and phosphates, labile C, potassium and probes for soil depth and compaction). Samples will also be packaged for laboratory analysis, for instance for total soil C.

Estimates of agricultural outputs (yields) will also be obtained through the household surveys, as well as through harvest sampling for 2-3 major crops from the agricultural fields. The number of fields monitored for yields will be such as to provide a reasonably constrained estimate of the mean yields for the crops making up 75% of the equivalent economic value of production (typically about 3 crops in a given landscape). It is anticipated that this will amount to around 30 fields per crop per Tier 4 landscape. The yield sampling will not follow the 'E-sample' grid approach, but will follow well-established protocols developed for various crop types (Nziguheba et al. 2011): for instance four strips of row-crop, each several meters long, randomly distributed in each field. The mean yields for the potentially long list of 'minor crops' will not be measured, but derived from farmer-reported estimates.

Households, Populations and Settlements

Tier 1: National or Regional Data

Tier 1 for the human-related observations consists of highly aggregated data from, for instance, national surveys and censuses, and the data field interpolated from them. An example of the latter is interpolated population density data, which distributes the enumeration area data at ~1 km resolution using proxy data such as lights-at-night, road density or dwelling counts.

In order to investigate links between environmental parameters, agricultural production and livelihoods, information on household livelihoods will be obtained from household surveys. This linkage can be done at the Tier 2 and Tier 4 sampling levels.

Tier 2: Household Surveys

At this level, VS will rely on the national level household surveys for the human wellbeing and agricultural production metrics; the frequency of sampling varies from country to country (annually to 3 year intervals). The households from the national surveys that fall within the VS region will serve as the sample, and this number is likely to range between 200 and 1000 households. The distribution of the household sample is unlikely to precisely match the ecological/agricultural stratification used for Tier 2 plots in transformed and untransformed landscapes, and is hard to change (and in any case, the samples will drift apart over time). Aiming for such alignment is a broad goal, but not a highly constrained requirement. It can be roughly achieved by placing the agricultural Tier 2 plots, in particular, preferentially into the areas where the household enumeration is done (these areas have themselves been randomly chosen). The 'accessibility' criterion applied to the natural landscape plots will tend to bias them towards somewhat populated areas. If the region is heterogeneous with respect to major agroecological zones, the farming systems will be quite distinct, in which case the

region will be subdivided by agroecological zones. The households within these subregions will be analyzed accordingly to investigate correlations between HWB, agricultural production and environmental metrics and indicators.

Tier 3: Continuously Recorded Social Data

No specific provision is made in VS for this tier. Examples could be a daily or weekly record of prices for particular commodities at a given village market; number of cases of particular diseases diagnosed at given clinics or hospitals; electricity used by particular towns; number of learners enrolled at particular schools etc.

Tier 4: Households within Sentinel Landscapes

The sample density from most existing (national) household surveys is insufficient to provide a sufficient sample size within the 10 x 10 km Tier 4 landscapes to achieve the Tier 4 objectives. Additional households will therefore need to be sampled in these landscapes by the VS teams. This should be coordinated so that the timing corresponds to that of the national surveys, allowing the data sets to be pooled. The target sample size is 30+ households per 10 x 10 landscape, randomly selected from a comprehensive list of households in the sample zone. This sample zone need not cover the entire 10 x 10 area – for instance, a 2 km buffer could be applied around the edges to ensure that all the households sampled do have the majority of their fields and resource areas within the 10 x 10 area. The household surveys will include a set of modules derived from the national LSMS survey to derive indicators of human wellbeing including consumption, food and nutritional security, health, gender, and education. In addition the surveys will include a list of agriculture and natural resource management questions, such as how much wood is used by household and from where it is obtained, what livestock is kept and where it is grazed, what water sources are used, where the household fields are, what is planted and what inputs are used.

For fields that farmers use that fall outside of the 10 x 10 landscape, those fields will not be measured as described in the Tier 4 area based sampling, but the survey will include questions about those fields.

In addition to the household level surveys, a few community level surveys will be conducted to get information such as market prices.

Freshwater Ecosystems and Water-Related Ecosystem Services

Extensive aquatic ecosystems (such as marshes) or floodplains are in principle sampled using the area-based frame for natural and semi-natural systems. It may require practical modifications to allow for accessibility during flooded periods, such as converting the 1 ha plot to a line transect that can be sampled from a boat. However, the moderate resolution land cover map area-based sample is not likely to pick up important but narrow linear features, such as riparian strips; as a result an

area-based sample stratified on this basis may miss them. Furthermore, landscape-scale losses of soil and nutrients scale with river flow, not strictly with area. Therefore flow-related elements of the aquatic systems need to be agglomerated using a flow-based approach rather than an area-based approach.

Water Yield

Tier 1

For macro-scale (regional) water yield, Vital Signs will rely on the existence of national systems of river flow monitoring, only supplementing them where nothing exists in a critical location (it is feasible to do so without building major structures). The guiding principle is that 80% of the flow generated by the region as a whole (as predicted by large-scale hydrological models) should be monitored on a daily or sub-daily basis. This requires a gauging station at or near the point at which the main rivers draining the region leave the region, reach the sea or a bounding lake, or leave a major impoundment, and (where necessary) at or near the point where main rivers enter the region. Judicious alignment of the regional boundaries with watershed boundaries will help.

For local-scale water yield (high-order watersheds, 10s to 1000s of km²), Vital Signs relies on spatially explicit, high-resolution (~5 km), remote sensing- and meteorology-driven 10-daily timestep hydrological models, calibrated to the total yield recorded by the exit-point gauges and whatever internal gauging exists.

Tier 2

No Tier 2 is envisaged specifically for water yield (see Tier 2 for water quality/river health). River heights on bridges that are routinely crossed during travel to and from field plots could be recorded as spot checks on hydrological model predictions. To be useful, these channels would need to be characterized for width, depth and flow rate.

Tier 3

For purposes of sensitive change detection and causal attribution, Vital Signs will establish two gauged micro-watersheds (<100 km²) per region in intensively monitored Tier 4 landscapes. Where feasible, each will be accompanied by a comparable 'control' micro-watershed in a predominantly natural or semi-natural area where there is some confidence that the control will remain in that state. Comparability of paired catchments is problematic even in the best of situations, however, so where a reasonable pairing is not possible, or land-use constancy in the control is not reasonably assured, the effort should rather be expended on more micro-watersheds in transformed or transforming landscapes, with the analytic approach being 'longitudinal' (i.e. change within the watershed over time) rather than comparison at a given time between two catchments.

A Vital Signs gauging station will make use of existing structures (bridges, dams or weirs) or a section of river reach with a stable profile. A vertical pipe will be firmly attached to the structure, and a

submersible pressure sensor will be suspended on a wire inside it, recording every 30 minutes. A synchronized barometric pressure sensor will be housed nearby in a secure location. In the case of Vital Signs micro-watersheds, an automated weather station gathering rainfall, temperature, humidity, wind velocity and shortwave radiation at 30-minute intervals be located within or near the watershed. The river profile and flow velocity will be surveyed at the time of establishment of the gauging station, and every 5 years thereafter (or more frequently if the profile is unstable). Flow measurements will be taken manually across the profile at various flow stages, as opportunity dictates, for construction of a flow-height curve (WMO 2010).

Table 5: River gauging stations will be supplemental to existing hydrological modeling in the regions, which varies from non-existent to quite good. Generally, the Tier 4-embedded micro-watersheds will be a Vital Signs responsibility.

Placement	Suggested number of gauging stations
Outflow (and inflow) of major regional rivers	4
Micro-watersheds	4

Water Quality

Tier 1

Since water quality modeling at a large scale is not yet feasible with acceptable confidence, Vital Signs depends heavily for its Tier 1 spatial water quality indirect (inferential or proxy) indicators, such as: predicted soil loss based on land cover class, soil type, fraction bare soils, rainfall intensity and slope, and regional nutrient balance (imports of N and P in the form of fertilizer, dry deposition and food less exports in harvested products).

Tier 2

Tier 2 consists of two elements: periodic bottle samples and occasional river health assessments. Monthly bottle samples will be collected at approximately 1 sample station per 20,000 km² of watershed area. The location of these sample points is distributed as follows:

1. At each of the macro-watershed flow gauging stations described above;
2. At each of the micro-watershed flow gauging stations described above;
3. At locations of 'convenience' for the remaining samples; either
 - River crossings that are repeatedly crossed by teams doing other Vital Signs fieldwork; and/or
 - Locations where permanent officials can have the sampling added to their job descriptions (such as ferry operators, dam custodians, water bailiffs etc).

Wherever possible, national water quality data, sample protocols and systems will be used, as well as national water quality laboratories to conduct the analyses. Vital Signs measurements are

supplementary to these, and only if the national authorities are unable to adjust their system to cover Vital Signs needs.

Table 6: The minimum set of Vital Signs water quality variables.

Variable	Notes
Location, depth, date, time, water temperature	At time of collection
pH	
Electrical conductivity	Proxy for salinity and Total Dissolved Salts
Dissolved inorganic nitrogen	NH ₃ ⁺ , NO ₃ ⁻
Phosphate	
Faecal coliform titre	
Total suspended solids	

The samples will be collected in 1-litre containers and stored in a darkened, chilled insulated box or a fridge until analysis within 48 hours (this means they would be collected on the return leg of sampling expeditions). Vital Signs is investigating rapid, in-field analyses for variables which can alter if the sample is stored. For instance, bacterial contamination may soon be detectable with specific kits, and the field chemistry kit being developed for soils may be modifiable to enable phosphates and nitrates to be analyzed almost immediately, in the field or nearby.

Tier 2a: River Health Assessments

These assessments are based on the presence and abundance of specific functional classes of aquatic organism. The protocol to be followed is the South African River Health protocol (Dallas 2007). The sample locations are determined by a stratified, quasi-random approach. The rivers are pre-classified according to their landscape position (upland or lowland), slope, flow regime and underlying geology. This classification is then overlaid on a road map to determine accessible points. There must be at least 2 assessment plots per river reach type.

Tier 2b: Rapid Riparian Survey

It is feasible to include an aquatic equivalent of the terrestrial rapid plot: at preselected river crossings, on roads frequently travelled by the sampling teams, teams can visually note flow depth, water color (clear, turbid, green), presence of alien vegetation, and odor.

Biodiversity

The above sampling frames are aimed at ecosystem services (including agriculture). While there are good reasons for believing that ecosystem services are supported by biodiversity, there is not a one-to-one relationship. Information on biodiversity data in the narrower, more traditional sense – the presence, absence and abundance of vertebrate and plant species – is expected by some stakeholders. Vital Signs does not set out to be a biological survey organization (most countries have

such organizations in the form of museums, herbaria and universities), but significant quantities and coverage of biodiversity-relevant information can be collected by the Vital Signs teams in the course of their ecosystem service work and travel. All teams must be trained in biological sample collection and equipped with a collectors permit and a basic collectors kit: sample bottles and preservatives; plant press; camera with date and GPS capable of 2:1 macro photography; background cloth; scale and color swatch; plant press and collector forms; binoculars; sample net; forceps; and GPS. An agreement must be made with one or more specialist institutes for the samples to be identified and curated, and the samples should find their way into the international collections databases (such as GBIF).

Biodiversity observations are usefully thought of as occurring at three levels of organization: the genetic, the species/populations and the ecosystem.

Genetic Level

Vital Signs activity at this level will initially be limited, but a close eye will be kept on rapidly emerging genomic and metagenomic techniques. One specific contribution from Vital Signs will be a characterization of field crops and domestic livestock at the variety level through the collection of local technical knowledge, backed up by photographs and genetic barcoding. This information will be collected in the course of agricultural sampling.

Species Level

Vital Signs Tier 1 role is to contribute to and access national and international sources of species presence/absence data, and, when enough data is available, periodically generate species distribution maps using niche-modeling software. This is so that species richness indicator coverages can be generated by broad taxonomic group of plants and vertebrates. The preferred approach is to merge such observations with all other observations, such as those collected by national agencies and GBIF nodes, and have the distribution maps generated by specialists.

Plants

The data collected on Tier 2 plots form a community species list with abundances, at least of dominant species. No special effort will be devoted to making complete species lists for Tier 2 plots, but if unknown species are encountered a specimen will be collected and pressed or a high-quality photograph will be taken (for later identification by a specialist). Tier 2b rapid plots can provide presence/absence data for dominant species. Field teams must be trained and assessed on their ability to correctly identify dominant tree and herbaceous plants and should have identification guidebooks with them. The panoramic photographs act as verification.

Birds

Vital Signs field teams should routinely keep ongoing and continuous bird checklists on their GPS-equipped smart phones. These can be agglomerated and added to BirdLife databases (typically by ¼

degree grid location). Citizen observers (particularly amateur ornithologists and wildlife clubs at schools) should be encouraged by Vital Signs through outreach and incentives to keep monthly checklists for their locations, which Vital Signs would enter into databases if they are unable to do so electronically themselves.

As part of the household panel survey linked to the agricultural survey, a record will be kept of the occurrence of crop losses due to birds (such as seed-eating quail), methods employed for control of birds (e.g., shooting or poisoning) and the consumption of wild-caught birds as 'bushmeat' (noting that in cases where this is illegal, under-reporting will be the norm).

In special circumstances (such as locations identified as Important Bird Areas or Ramsar sites) a case might be made for periodic standardized bird transects, counts or dawn chorus sound recordings. These are not part of the basic Vital Signs package and would need to be implemented on a case-specific basis, usually in collaboration with partners.

Mammals

The approach will be tailored to specific regions, depending on the degree to which they have mammal populations, the importance of these populations to ecosystem services (e.g. bushmeat and wildlife-based tourism), the potential impacts of agriculture on endemic wildlife or key wildlife migration corridors and the animals' damage potential for agriculture (rodents, elephants, primates). The minimum is 1) the maintenance of geographically explicit checklists based on observations (including roadkill or bushmeat on sale or display); 2) the recording of mammal-origin damage in agricultural landscapes (elephants, wild pigs and primates are common causes) and 3) the use of mammals as a household nutritional or economic resource ('bushmeat'). In specific high-importance cases, such as protected areas or endangered species, camera-trap grids can be deployed for 30-day periods, using the TEAM protocol. Aerial census surveys of large mammals are routinely conducted in some Vital Signs regions, either for the whole region or for specific subregions such as protected areas. Vital Signs should negotiate access to these data, as they also often contain valuable data on livestock densities.

In regard to bushmeat, the measurements we are after relate to the sustainability of bushmeat harvest: amount harvested, based on household surveys; the importance of bushmeat for household nutrition; and impacts on diversity of species.

Reptiles and Amphibians

No special provision is made in Vital Signs beyond entering incidental observations made by field teams into international databases (in cases where identification is clear and backed up with a photograph or specimen).

Invertebrates

A record of pest insect damage to crops or forage will be kept in conjunction with household/agricultural survey, along with a household record of the use of wild-harvested insect foodstuffs (termites, caterpillars and honey) and the occurrence of insect-borne diseases (malaria, trypanosomiasis). In areas where honey is an important element of the rural economy a relationship should be developed with apiarist farmers to record yields geospatially within Tier 4 landscapes, both as a resource and as an indicator of pollinator abundance. Tier 2a and 2b rapid samples should note the presence of active hives in sampled plots.

The following strategies provide additional possibilities, but are *not* required in the standard Vital Signs package:

- When Vital Signs field teams camp at night they could set up light traps for night-flying insects (anesthetized samples would be preserved for identification by specialists).
- Vital Signs field vehicles could be equipped with a removable standard-sized nylon ('flyscreen') net over their radiator grille, which can be replaced daily along with a record of the distance driven and the route taken. These samplers can be scored for insect number and type and then cleaned and recycled, or they can be rolled and stored in a tube for expert identification (possibly they could act as a metagenomic sample).
- AfSIS sampling includes a module on soil invertebrate macrofauna.

Ecosystem Level

The Tier 1 landcover maps, Tier 2a plots and (to a lesser extent) the Tier 2b rapid plots will put Vital Signs in a position after the first full cycle of data collection (3-5 years) to generate improved ecosystem maps (including the aquatic ecosystems) for the regions at 1:50 000 scale (resolution 500 m), based on the multivariate analysis of the ~500 tier 2a plots and ~5000 Tier 2b plots.

Remote Sensing

Remote sensing is a key resource for both Tier 1 and, at a much higher resolution, Tier 4. Tier 1 consists of regionally complete ('wall-to-wall') automated land cover classification at approximately 500 m resolution. It will take place at 5-year intervals (or more frequently), to at least the second level of a LCCS hierarchy. Moderate-resolution multi-temporal satellite sources will be used (e.g. MODIS, MISR, VIIRS, SPOT-Vegetation). A third level LCCS classification will be inferred based on likely species composition, based on (1) a priori knowledge (vegetation maps) and (2) niche models and maps built from Vital Signs data. The second-level classes form the initial basis of area-based stratification and agglomeration in Vital Signs. Once there is sufficient confidence in the Tier 3-validated ecosystem maps, the level 3 classification can also be used for stratification and agglomeration and reporting.

The Tier 4 landscapes will be based on high-resolution (HR, ground sampling distance of 1 m or less in the PAN waveband) images of at least 10 x 10 km. The entire landscape will be automatically

classified using eCognition-type approaches, followed by manual adjustment of the classes. The classes will follow the habitat classification proposed by the EU FP7 EBONE project (Bunce et al. 2012), which was in turn based on work in the EU FP5 BioHab project. Ebone extracts 1 x 1 km squares as its statistical units, and this is also consistent with the BIOTA 1 x 1 km biodiversity sample. It is not cost effective to acquire and process separate HR images for a stratified or regular 1 x 1 km² sample set over an entire region. About 16 more-or-less statistically independent (i.e. not adjoining) 1 x 1 km squares can be placed in a 10 x 10 km image. Statistics are to be estimated at this scale, but this approach is bedeviled by the problem that the small number of images tend to be a biased sample of the region overall.

Table 7: Summary of remote sensing platforms for Vital Signs purposes.

Sensor	GSD	Spectra	Swath	Cost per scene ¹
High resolution (~ 1 m): suitable for landscapes				
GeoEye-1	0.41 PAN 1.65 MSS	Blue, Gr, Red, NIR	15.1 km	\$1250-2500
Ikonos	0.82 3.2	Blue, Gr, Red, NIR	11.3 km	\$1000-2000
Quickbird	0.7 PAN 2.8 MSS	Blue, Gr, Red, NIR	16.5	\$1400-2000
Worldview 1	0.5 PAN 2 MSS	PAN	14 km	\$1400-2000
Worldview 2	0.5 PAN 2 MSS	Blue, Gr, Red, NIR	14 km	\$1400-2000
SPOT 6&7	1.5 PAN 8 MSS	Blue, Gr, Red, NIR	60 km	
Cartosat IRS	0.8 m	PAN	9.6	
Digital aerial photo	0.5 m	Blue, Gr, Red, NIR	~1 km, but can be stitched together	
Near-high resolution (5-30 m): may work for some landscapes, areas of rapid change				
Aster	15 m	14 bands VIS,IR	60 km	Not commercial, research only
ResourceSat IRS	5.8m PAN 24m MSS	Blue, Gr, Red, NIR	30 km	
Landsat 7 (& 8 after Dec 2012)	15m PAN 30m MSS	Blue, Gr, Red, NIR MIR	165	No cost
Moderate resolution (300-500 m): suitable for regional land cover mapping				
MODIS	500 m	18 bands	2200, daily with 10-day composite	No cost
MISR	275 m	Blue, Gr, Red, NIR	400, 10-daily	No cost, but not widely available
MERIS (till 2012) Basis of JRC Globcover 2005	300 m		2000, daily with 10-daily compositivity	No cost, but instrument failed Feb 2012
Low resolution (>1 km): not generally suitable for VSA; could help patch moderate resolution images				

AVHRR	1100 m	Blue, Gr, Red, NIR	Daily	Southern Africa LAC from SANS GAC from NASA
SPOT Vegetation	1150 km	Blue, Gr, Red, NIR	2200 km, daily with 10-daily composite	No cost VTI
MSG	~ 5 km	Blue, Gr, Red, NIR	Geostationary: all of Africa	Every 15 minutes

1. The costs in the above table are for July 2012 from SA National Space Agency, which has an archive for southern Africa. Digital Globe or other sources are alternate supplies; the costs should be similar. The first value is for an already-archived scene, second is for a custom acquisition.

In addition to the images required for land cover classification, running the models on which the indicator layer of Vital Signs depends will require the following remotely-sensed or hybrid remote sensing data assimilation datasets. Most are available at little or no cost, but require significant effort to obtain and subset on a repeated operational basis. For the next several years, they will be most efficiently extracted and packaged by a partner organization in Europe or North America.

Table 8: Remote sensing needs and sources not directly related to land cover mapping. The bold entries are the user requirement. Sources are in order of preference.

Dataset	Spatial resolution	Frequency	Source
Digital Elevation Model	30 m horizontal 30 m horizontal, 1 m vertical (relative)	Once	SRTM (CGIAR version) ASTER
Flow drainage network	1 km	Once	FAO/GEONetwork
Rainfall	5 km 0.0375 deg(5 km) 0.1 deg (~10 km)	10-daily (dekadal) 10-daily Daily	TARCAT v2 ^a CPC/FEWS RFE2.0 ^b TRMM (before 2010) ^c
FAPAR	300 m 300 m 1000m	10-daily 10 daily (composite of daily)	MISR SPOT vegetation
Albedo	300 m 300 m 500 m	10-daily 10-daily	MISR -HR ^d Modis
Burned area	300 m 500 m	10-daily Daily	Modis
Near-surface air temperature	5 km 5 km	10-daily 10-daily means of daily max and min	NCEP
Relative humidity	5 km 5 km	10-daily 10-daily (mx+mn)/2	NCEP
Near-surface wind speed	5 km 15 km	10-daily 10 daily mean	NCEP
Cloud cover and type	5 km	10 daily composites	

	4 km	30 min fundamental	MSG
Actual evaporation	5 km	10- daily	EARS ^e CPC/FEWS
Population distribution	1 km	Annual	CEISIN
Roads network	250 m	5 years	Commercial GPS navigation
Protected area network	500m	Continuously updated	WCMC, national conservation authorities, NGOs

- a. University of Reading TAMSAT project
- b. Climate Prediction Center, NOAA, with USAID Food Early Warning System
- c. NASA
- d. South African National Space Agency
- e. A commercial company in the Netherlands, associated with University of Delft

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