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Insight

GPS and GIS Methods in an African Rain Forest: Applications to Tropical Ecology and Conservation

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ABSTRACT

Since the completion of the Navstar Global Positioning System (GPS) in 1995, the integration of GPS and Geographical Information Systems (GIS) technology has expanded to a great number of ecological and conservation applications. In tropical rain forest ecology, however, the technology has remained relatively neglected, despite its great potential. Notwithstanding cost, this is principally due to (1) the difficulty of quality satellite reception beneath a dense forest canopy, and (2) a degree of spatial error unacceptable to fine-scale vegetation mapping. Here, we report on the technical use of GPS/GIS in the rain forest of Kibale National Park, Uganda, and the methodology necessary to acquire high-accuracy spatial measurements. We conclude that the stringent operating parameters necessary for high accuracy were rarely obtained while standing beneath the rain forest canopy. Raising the GPS antenna to heights of 25–30 m resolved this problem, allowing swift data collection on the spatial dispersion of individual rain forest trees. We discuss the impact of the 1996 Presidential Decision Directive that suspended U.S. military-induced GPS error on 1 May 2000, and comment on the potential applications of GPS/GIS technology to the ecological study and conservation of tropical rain forests.

KEY WORDS: Kibale National Park, Uganda, biodiversity conservation, canopy interference, differential correction, frugivores, geographic information systems, global positioning system, seed dispersal, spatial ecology, tropical rain forest, vegetation mapping.

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INTRODUCTION

The occupation and utilization of space is implicit to any ecological investigation and is central to ecological theory (Dale 1999, Folt and Burns 1999). In this regard, the spatial dispersion of trees has long captivated ecologists (Wallace 1878) and has stimulated decades of research (Diggle 1979, Condit et al. 2000, Plotkin et al. 2000). In the tropics, the mapping of individual trees is beginning to yield great insight into patterns of recruitment limitation, seed dispersal, and tropical tree diversity (Wills et al. 1997, Hubbell et al. 1999, Condit et al. 2000, Harms et al. 2000). Indeed, the work of Harms and colleagues (2000) is so compelling that, in the words of Howe and Miriti (2000:434), there is now "no question: seed dispersal matters." However, although this study underscores the hypothesized relationship between patterns of vertebrate seed-dispersal and tropical species diversity (see Howe 1989), it also calls attention to the sixth great mass extinction currently facing tropical ecosystems (May 1999, Pimm and Raven 2000). Forest plotting and the measurement of species diversity are thus important components of forest conservation and management (Hubbell and Foster 1983) because, as Plotkin et al. (2000) emphasize, these techniques are poised to answer controversial questions such as: How does habitat loss relate to species extinction of both vertebrates and plants? What is the best possible design of a natural reserve to maximize the number or genetic diversity of surviving species?

Forest plotting, however, is often tedious work. Classic methods of ground-based mapping frequently involve triangulation from a known point, which, in a rain forest, may involve extensive labor without being outstandingly accurate. Distance accuracy using reconnaissance-type mapping is at best only 1 part in 80 (4.5°) with a hand-held compass, and 1 part in 300 (1.2°) with a staff-held forester's compass (Mosby 1959). These techniques have served tropical ecology well, but mapping accuracy and efficiency can be greatly improved today by utilizing Global Positioning Systems (GPS) and Geographic Information Systems (GIS) technologies. The relatively recent development of GPS and GIS technologies appear ideally suited to conservation efforts because they empower ecologists to expeditiously acquire, store, analyze, and display spatial data on organisms and their environment (Johnston 1998, Wadsworth and Treweek 1999). For example, in Bwindi National Park, Uganda, GPS was used to determine that mountain gorillas (*Gorilla gorilla beringei*) preferentially sleep in areas outside park boundaries (Goldsmith 2000). This finding has important conservation implications because many plant species may rely on both gorillas and their sleeping sites for seed dispersal and seedling recruitment (Tutin et al. 1991, Rogers et al. 1998). Simply enlarging the perimeter of Bwindi to include these sites would therefore seem an important step to preserve both the vulnerable gorillas and the diversity of the system as a whole. In this regard, the application of integrated GPS/GIS technology to habitat utilization models is particularly strong because it is capable of identifying those habitats most at risk of human encroachment and essential to species' demographic success (e.g., Breininger et al. 1991, 1995, Duncan et al. 1995).

When using GPS in a forest, however, one is faced with two critical problems: (1) a 10–30 m spatial error presently found in autonomous GPS coordinates is unsuitable for plotting and differentiating individual trees, and (2) a dense forest canopy may pose a significant physical barrier to accurate GPS satellite reception and data acquisition (Wilkie 1989, Petersen 1990, D'Eon 1995, Wills 1996, Phillips et al. 1998). Our objective in Kibale National Park, Uganda was to mitigate these problems in a wet and remote environment. We were interested in the rapid and highly accurate (i.e., ± 1-m) plotting of individual trees in order to understand how scatter vs. clumped patterns of vertebrate seed dispersal (sensu Howe 1989) account for the spatial dispersion of adult trees

(N. J. Dominy and B. Duncan, *unpublished manuscript*). Our aim here is to report on the feasibility and systems capabilities of a 12-channel backpack GPS with satellite-based differential correction in a rain forest environment. We believe that the findings may aid effective management decisions by increasing the efficiency of data collection and analysis, reducing spatial error, reducing the volume of archived records, easing data management, and increasing information sharing between tropical ecologists.

Definition of GPS

The Navstar Global Positioning System (GPS) refers to the group of 24 geosynchronous satellites owned and maintained by the U.S. Department of Defense (USDOD). Equipped with atomic clocks, each satellite emits a unique radio signal that is received by a GPS receiver on Earth. The quartz clock in a GPS receiver is calibrated to a satellite′s atomic clock via information imbedded in the GPS signal. Because each GPS receiver generates the same unique code at the same time as each satellite, it is able to measure the time lag between radio signals sent and received. Because radio signals travel at a standard speed (299,460 km/s), a precise Earth location is thus a trigonometric equation solving for the intersection of four spheres with known radii (the radius being the measured distance between a receiver and satellite). Therefore, a minimum of four accurate distance measurements is theoretically required to determine a precise three-dimensional location on the surface of the Earth. Because each of six orbital planes contains at least four satellites inclined to the equator at an angle of 55 degrees, all areas of the Earth have at least four satellites visible at any given time.

GPS data are usually expressed as latitudes and longitudes relative to a mathematical model called the World Geodetic System 1984 datum (or WGS-84). Coordinates in the WGS-84 model are based on both an origin point and the GRS-80 ellipsoid, the standard most closely approximating the shape of the Earth. Prior to 1 May 2000, the greatest source of GPS error was called Selective Availability (S/A), which referred to ephemeris errors (epsilon) and satellite clock errors (dithering) deliberately induced by the U.S. Department of Defense. Autonomous GPS accuracies of 10−30 m were restricted to all except those authorized by the U.S. military and its allies. The combination of S/A and other sources of error (e.g., ionospheric and tropospheric delay) resulted in 95% of all civilian GPS positions being somewhere within 100 m of truth (Trimble Navigation 1998). Although the recent presidential decision to remove S/A now improves civilian GPS accuracy to 10−30 m (McDonald 1999), differential correction is still necessary to compensate for error sources preventing the accuracy at < 1 m possible with current GPS technology.

Definition of GIS

Geographic information systems are an information technology with the capacity to store, analyze, and display both spatial and nonspatial data (Parker 1988). Although some modern Computer Aided Design (CAD) systems can link geographic features with attributes in a database, they are considered graphic systems only (Cowen 1988). The utility of GIS (Scholten and de Lepper 1991) is more sophisticated in:

1. storing, managing, and integrating spatially referenced data relating to points (e.g., individual trees), lines (e.g., rivers, roads), and polygons (e.g., forest boundaries, habitat types, territorial ranges);
2. conducting spatial queries (e.g., searching for areas in which a particular species or feature occurs);
3. engaging in geographic analysis (e.g., statistical analysis of relationships between habitat and reproductive success); and
4. displaying data in the form of high-quality maps.

METHODS

Spatial data were collected in order to analyze the influence of seed dispersal by large frugivores on the spatial dispersion of adult rain forest trees (N. J. Dominy and B. Duncan, *unpublished manuscript*). Here, we describe our use of GPS and GIS technology to map individuals of three tree species representing an elephant−ape−monkey continuum of seed dispersal. They are, respectively: *Balanites wilsoniana* (Balanitaceae), *Chrysophyllum gorungosanum* (Sapotaceae), and *Uvariopsis congensis* (Annonaceae).

Site description

The study was located in the Kanyanchu research area (~1300 m a.s.l.) of Kibale National Park, Uganda (0°13′ N to 0°41′ N and 30°19′ E to 30°32′ E). Forest canopy typically ranges from 25 to 40 m, although some trees may obtain heights of 50 m. Vegetation classification ranges from moist evergreen forest (but closely related to moist montane forest) to lowland tropical rain forest, with affinities to both montane and mixed tropical deciduous rain forest (Langdale-Brown et al. 1964, Struhsaker 1997). Mean annual rainfall is 1700 mm (1990–1996; C. A. Chapman and L. J. Chapman, *unpublished data*) and bimodal in distribution, occurring in two distinct rainy seasons: March–May and August–November.

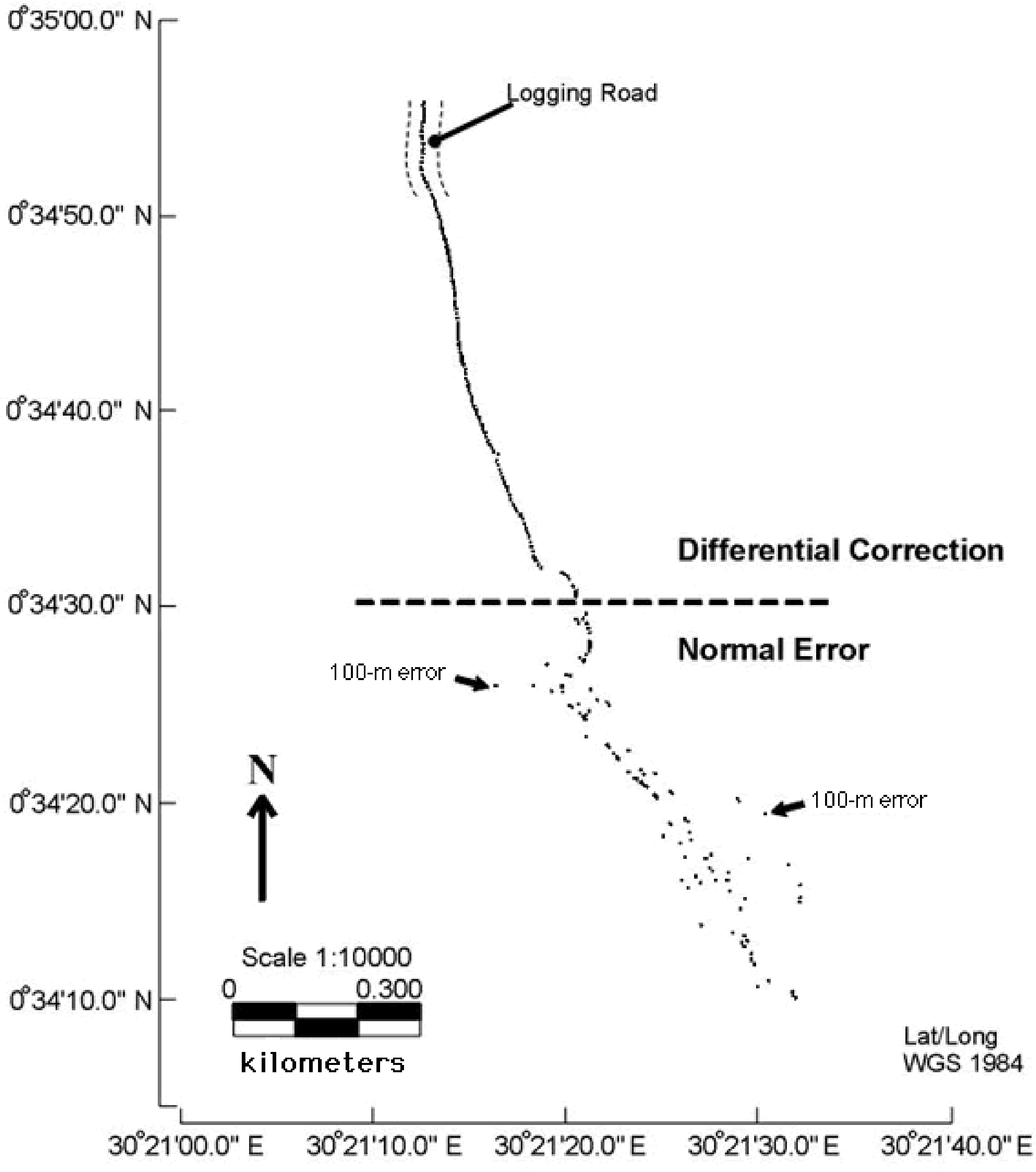
Equipment and data collection

From April to July 1999, we used a 12-channel GPS Pathfinder Pro XRS System (Trimble Navigation 1998) equipped with subscription to a satellite differential correction service (Fugro-OmniSTAR, Houston, Texas). The selection of this unit was based on the demands of a rain forest environment and the need for the highest possible accuracy (the unit is sub-meter capable). In addition to being light in mass (1.35 kg) and battery powered, this backpack GPS has several other features that are suited to meet those needs: (1) the capacity to simultaneously track 12 satellites; (2) real-time differential correction capability; (3) a rugged, waterproof housing; and (4) built-in, multipath rejection technology.

Data were collected using the manufacturers′ suggested critical settings. The Position Dilution of Precision (PDOP) mask was set to <6.0, the Signal-to-Noise (SNR) mask was set to >6.0, and the Elevation mask was set to 15°. PDOP is a measure of how clumped the satellites are in space and how strong the trilateration base will be for determining a position on Earth. The more evenly distributed the satellites are in space, the better the trilateration base and the lower the PDOP number. The SNR is a measure of satellite signal strength; hence, the higher the number, the stronger the signal. The elevation mask helps to prevent the GPS unit from using unfavorable satellites by eliminating those that are low on the horizon. After configuring the critical settings, we established a link between the Pro XRS and the satellite differential service (XSAT satellite, 1538.053 MHz, data rate: 2400 bps). Given an ideal physical environment and these configurations, Fugro-OmniSTAR specifies the expectation of 1-m data for study locations in Africa (M. Huff, *personal communication*). This is because OmniStar's 10 regional base stations around the southern half of Africa and their unique "Wide Area Solution" give any user, regardless of distance or location, approximately the same 1-m accuracy (Huff 1995).

We began data collection with a series of tests aimed to assess equipment function. To compare differences between differentially corrected and uncorrected data, we walked along a relatively open and unobstructed logging road and collected a single location point every 7 s. We then plotted and analyzed the differences between uncorrected and corrected data to determine whether the difference was within the expected range of USDOD specifications for autonomous GPS (Fig. 1). After satisfactory results, we began to map individual trees when Trimble′s Quick Plan software indicated optimal conditions (i.e., at times during the day featuring the greatest number of satellites with PDOP <6.0).

Fig. 1. Comparing differentially corrected GPS data vs. normal GPS data while walking along a widely cut logging road in Kibale Forest, Uganda. At the time of this study, Selective Availability resulted in points 50–100 m from truth. As of 1 May 2000, normal error was reduced to 10–30 m.

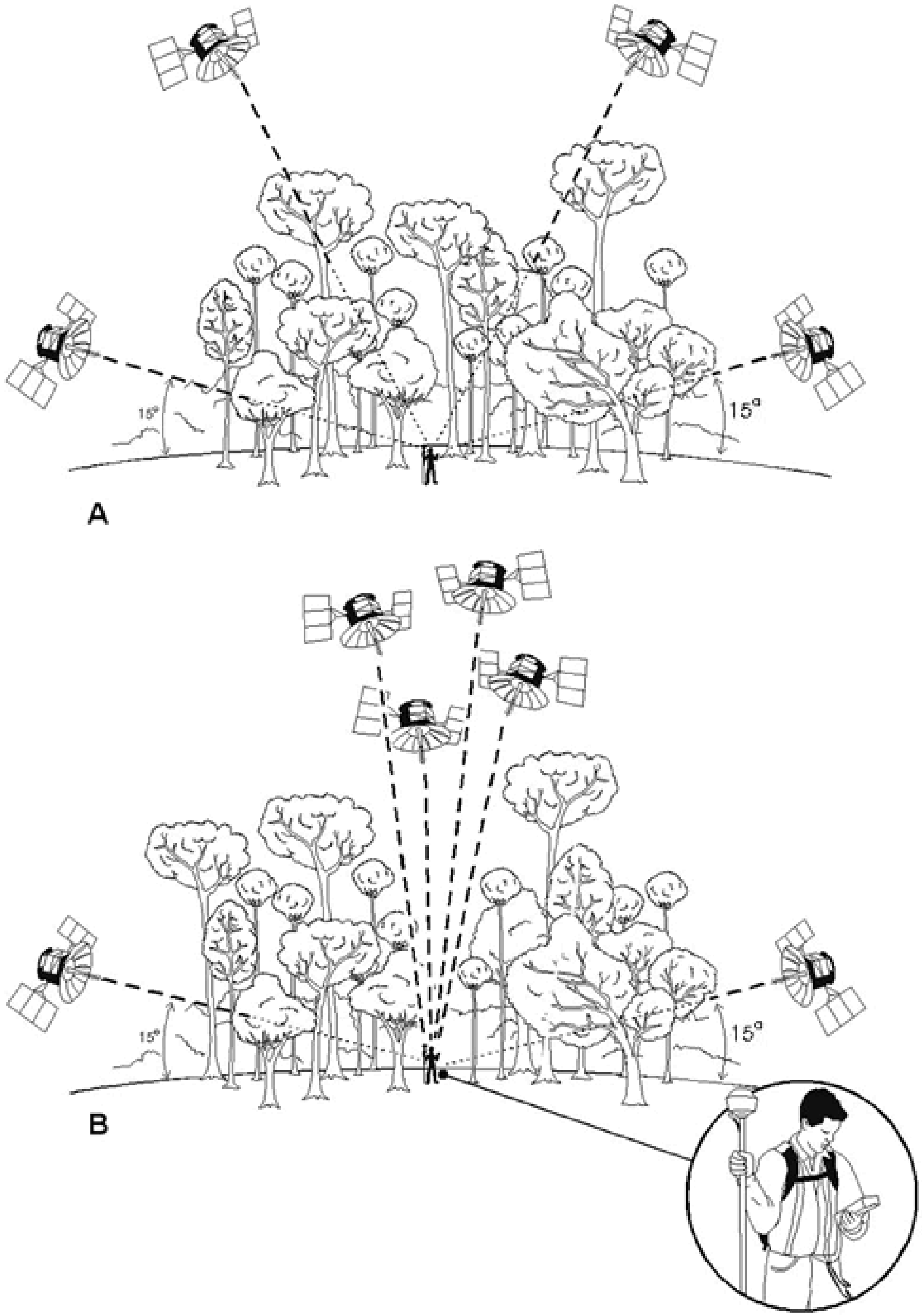

0°35'00.0" N
0°34'50.0" N
0°34'40.0" N
0°34'30.0" N
0°34'20.0" N
0°34'10.0" N
Logging Road
Differential Correction
Normal Error
100-m error
100-m error
N
Scale 1:10000
0
0.300
kilometers
Lat/Long
WGS 1984
30°21'00.0" E
30°21'10.0" E
30°21'20.0" E
30°21'30.0" E
30°21'40.0" E

To measure the positions of trees, we placed the GPS antenna against individual boles in both undisturbed forest and near canopy gaps. If neither GPS nor differential (DGPS) readings were obtained at ground level, trees were ascended using a safety belt and Buckingham tree climbers (essentially, steel gaffs and shanks strapped to the feet). Data on the attributes and spatial location of individual trees were then downloaded onto a portable laptop computer and exported into GIS software (ArcView version 3.1, Environmental Systems Research Institute, Redlands, California, USA).

RESULTS

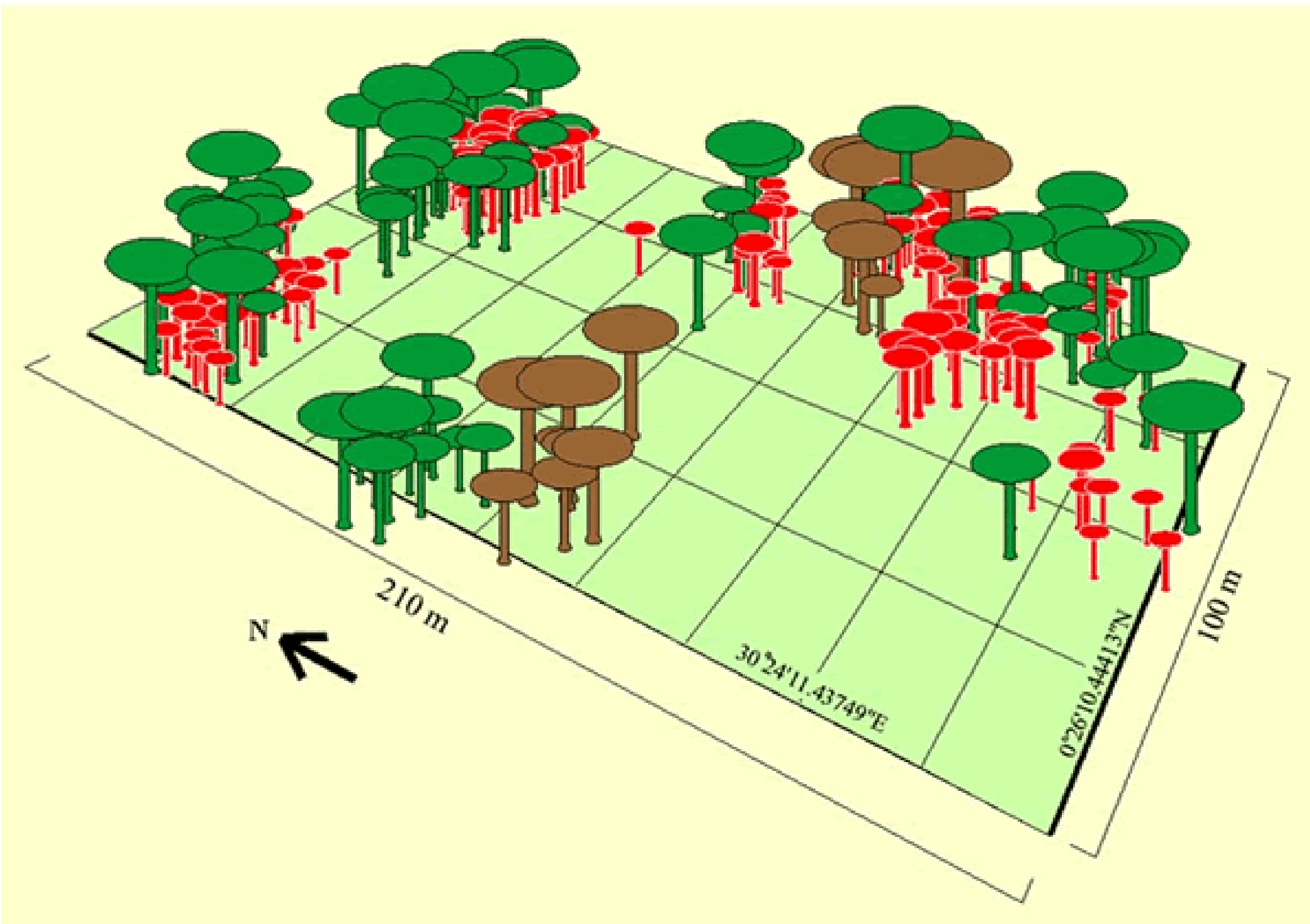
In conditions under which the sky was relatively open and free of obstruction, a minimum of four satellites in optimum position and signals of optimum strength were always located and tracked, allowing consistent collection of high-accuracy data in real time. Often, however, ground-based attempts to log differentially corrected data points beneath the forest canopy resulted in total failure. Although the GPS receiver was, at times, able to locate the required minimum of four satellites, the narrow signal parameters needed for high-quality, differentially corrected positions were rarely obtained. Attempts to plot trees in the forest interior failed because the SNR became so convoluted by heavy foliage that even the minimum requirement of tracking four satellites was rarely achieved (Fig. 2A). In trials with the GPS antenna positioned near canopy gaps, the hand-held data logger indicated favorable SNR levels, but these were confounded by conditions of poor satellite positioning or high PDOP (Fig. 2B). In an attempt to mitigate these factors, we climbed trees in order to escape as much signal interference as possible. From a height of 25−30 m, the SNR increased and PDOP decreased sufficiently to allow high-accuracy DGPS measurement. This strategy always worked, although the GPS receiver sometimes required 10−15 min to locate satellites with the optimum PDOP required for collecting the highest quality measurements. In 135 DGPS measurements, we tracked 6.65 ± 0.92 satellites (mean ± 1 SD), and PDOP was 2.48 ± 0.75.

Fig. 2. GPS satellite signal reception and rain forest canopy interference. (A) Despite favorable satellite geometry, attenuation of the satellite signal (SNR) by dense foliage makes data collection impossible. (B) Although six satellites are on the horizon, only four are usable, due to signal attenuation by the canopy. SNR from satellites passing near canopy gaps is optimal, but poor orthogonal positioning results in high PDOP, which makes data collection unreliable.



The map ([Fig. 3]) produced by our methods shows the degree to which high-accuracy GPS data can be plotted with the aid of GIS technology. *Uvariopsis congensis* (Annonaceae), for example, was exceptionally dense: the modal distance between nearest conspecifics was 3.95 m (minimum 0.023 m). Every tree was represented by a single point because, in addition to the sheer time commitment required to climb trees, the degree of error was considered minor relative to the circumference of the tree itself.

Fig. 3. Map of trees under study: red, *Uvariopsis congensis* (Annonaceae); green, *Chrysophyllum gorungosanum* (Sapotaceae); and brown, *Balanites wilsoniana* (Balanitaceae). This figure, from Lucas et al. (2001), is used with permission.



DISCUSSION

In Kibale Forest, we experienced one of the main limitations of GPS technology. Dense forest canopy posed a significant physical barrier to quality GPS signal reception. Although researchers have described using GPS technology beneath the rain forest canopies of Africa (Wilkie 1989), Southeast Asia (Wills 1996), and Central America (Phillips et al. 1998), none has attempted to mitigate induced or inherent signal errors. Even if their measurements were repeated now in the absence of S/A, their methodologies did not include differential correction and would thus result in an error of at least 10–30 m (McDonald, 1999). Although this degree of error is probably acceptable to many ecological applications, fine-scale vegetation mapping requires high levels of spatial accuracy. It is unlikely that traditional mapping techniques would have produced the differentiation between trees reported here.

Our solution to achieving high spatial sampling accuracy in a tropical rain forest environment is just one of many that can be taken using today's available technology. We chose to use a satellite subscription service for producing our DGPS measurements, rather than using a base station. A base station is an additional GPS receiver with an antenna stationed in an area that has an unobstructed view of the sky and is relatively close to the study site (at least within 1500 km, or 250 km for the highest accuracies). Ideally, the antenna of this unit would be surveyed in so that its position would be known with precision. A base station operates simultaneously while the rover unit is collecting field data. Because the base antenna is on a known position, geographically close, and running at the same time that the rover is collecting data, its files can be used to remove unwanted error inherent in the GPS signal. This is referred to as post-processed differential correction, because the corrections are applied after field data collection is completed.

In a typical collecting environment, post-processed GPS data will yield greater accuracy than data produced by real-time differential correction techniques. However, one thing we knew prior to commencing work in Kibale Forest was that we would not be working in a typical GPS collecting environment: a dense, multilayered forest environment is one of the most challenging for this technology. We quickly ruled out post-processing using a separate base station, reasoning that we would need to purchase two units instead of one. This was possible, but not likely, considering our research budget. Moreover, it would be difficult to find a surveyed locality (a monument or survey marker) with known coordinates on which to place the antenna. Although a fixed reference may be obtained with a second unit collecting and averaging data, this is time consuming and unlikely to produce greater accuracy than a real-time differential correction service. Finally, concerns regarding theft contributed to the decision to avoid use of a base station. We chose the Trimble Pro XRS because of its proven performance and suitability for real-time differential correction.

Although the methods described here involved climbing trees, a tiring and arguably dangerous pursuit, we believe that outfitting the GPS antenna with a telescoping pole would achieve the same results. Although using a telescoping range pole could be very effective and efficient if used properly, there are several considerations when elevating the antenna. The first is simply being able to control and balance the elongated range pole, a task that may be facilitated with an assistant and/or supporting vegetation. The second consideration is protection of the antenna and cable from damage by vegetation. Lastly, the Pro XRS antenna cable may not exceed 30 m without an inline repeater.

In a rain forest environment, however, the manufacturer’s accuracy specifications may only be used as a guideline. Absolute accuracy may only be gauged by comparing DGPS measurements made using field techniques with a point of known coordinates. Unfortunately, we were unable to locate a nearby locality with known, highly accurate coordinates, so this comparison was not made. Real-time DGPS techniques and elevating the antenna may have contributed to the overall error, but, despite this, we are confident that our measurements fall within a 1–2 m error range, with the majority being closer to 1 m.

Speculation

What is the value of rapid, high-accuracy mapping techniques in the rain forest? Recent studies analyzing plots of rain forest trees are now yielding great insights into patterns of recruitment limitation, seed dispersal, and tropical tree diversity (Hubbell et al. 1999, Condit et al. 2000, Harms et al. 2000). The patterns of seed deposition, seedling demography, and adult tree recruitment are critical to making sound conservation decisions regarding tropical rain forest habitats (Hubbell and Foster 1983). This is particularly true in light of the probable co-dependence of many tropical trees on large-bodied frugivores vulnerable to poaching and habitat destruction (Chapman and Chapman 1995, Chapman and Onderdonk 1998, Balcomb et al. 2000). With ‘biodiversity hotspots’ (sensu Myers et al. 2000) rapidly shrinking in area, it is essential to understand how seed-processing by these animals affects forest composition. In this regard, the main advantage of GPS/GIS technology is its speed. In addition, the integration of GPS/GIS technology with habitat utilization models is particularly strong, because it is capable of identifying those habitats most at risk of human encroachment and essential to species demographic success (e.g., Breininger et al. 1991, 1995, Duncan et al. 1995). To this end, the recent miniaturization of GPS receivers for use in radio collars (Moen et al. 1996) will obtain animal ranging data faster and far more accurately than would cumbersome radiotelemetry equipment. In sum, the methods described here allow for the application of GPS/GIS to rapid and fine-scale vegetation mapping of rain forest environments. We believe that the utility of this technology to address important empirical and theoretical issues, along with the speed and accuracy of the methods, are well worth the effort and cost.

RESPONSES TO THIS ARTICLE

Responses to this article are invited. If accepted for publication, your response will be hyperlinked to the article. To submit a comment, follow this link. To read comments already accepted, follow this link.

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