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Digital data collection in forest dynamics plots

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Summary

1. Computers are widely used in all aspects of research but their application to in-field data collection for forest plots has rarely been evaluated.

2. We developed digital data collection methods using ESRI mapping software and ruggedized field computers to map and measure ~30 000 trees in two 4-ha forest dynamics plots in wet and dry tropical forest in Hawaii. We then compared our data collection and entry effort with published values for other forest dynamics plots with the same tree measurement protocols to estimate the efficiency of our methods relative to the more typical use of paper data collection sheets.

3. In-field data collection effort was comparable for all plots. However, use of digital methods resulted in an average 11·8% reduction in total effort due to reduced secondary data entry time.

4. The digital data collection methods described in this article can be applied to a wide range of ecological projects, especially long-term research or monitoring projects where mapping can be integrated into data collection.

Key-words: Center for Tropical Forest Science, digital data collection, ecology methods, forest dynamics plots, Hawaii

Introduction

Considerable amounts of money and time are often invested in data collection and entry, and data quality can affect the analysis and conclusions of a study. Thus, it is worthwhile to explore options that may increase efficiency and accuracy. The use of digital methods is well described in the medical literature (Abernethy *et al*. 2008; Hayrinen, Saranto, & Nykanen 2008; Borycki *et al*. 2009; Fonseca, Ribeiro, & Granja 2009; Mador & Shaw 2009; Ohmann & Kuchinke 2009), but there are relatively few studies that discuss these methods for ecological research projects (Logan & Smith 1997; Elzinga *et al*. 2001; Southwell *et al*. 2002; Waddle, Rice, & Percival 2003; Stoleson *et al*. 2004; van Tamelen 2004). Digital data collection has become standard in national vegetation monitoring networks, such as the USDA Forest Service's Forest Inventory and Analysis Program (http://fia.fs.fed.us/; Forest Inventory and Analysis National Core Field Guide, Volume I: Field Data Collection Procedures for Phase 2 Plots, Version 4.0, 2007). However, most forest plot studies use written methods and we are not aware of studies that have shown the efficiency of electronic data collection methods as an alternative to paper-based data collection methods in forest plots. Indeed, a Web of Science search on 'digital data collection' returned over 1500 citations of which more than 60% were related to medical research and most of the remainder discussed applications for climate and remote sensing research. Of the few articles that discussed ecological research, most focused on wildlife research (Logan & Smith 1997; Elzinga *et al*. 2001; Southwell *et al*. 2002; Waddle, Rice, & Percival 2003; Stoleson *et al*. 2004; van Tamelen 2004). For example, Waddle, Rice & Percival (2003) and Elzinga *et al*. (2001) outlined the qualitative benefits and concerns associated with digital data collection. Others have described methods to integrate the collection of location, audio, and other types of data by using Personal Digital Assistants (Logan & Smith 1997; Southwell *et al*. 2002; Stoleson *et al*. 2004; Travaini *et al*. 2007). All concluded that these systems were cost-effective and increased data collection efficiency. However, to our knowledge, only one article directly compared efficiency of digital vs. written methods for collecting ecological data; in this study, digital vs. standard calipers were compared for measuring crabs and found that digital methods were three times faster than written methods and that data quality was comparable (van Tamelen 2004).

Electronic data collection holds great promise for enhancing ecological research capacity, yet researchers may be reluctant to adopt digital methods for many reasons including concerns

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of losing large amounts of data, the money and time needed to buy and implement a new system, the weather-resistance of electronic devices, and lack of familiarity with digital options. Some would question any investment in additional training once a field crew is trained and familiar with a written system. However, digital technology has improved greatly in recent years to become more secure, rugged, economical and user-friendly. These new systems have the potential to improve efficiency and increase data accuracy for vegetation monitoring and ecological studies.

We quantified the increase in efficiency resulting from digital collection methods for mapping and measuring trees in large-scale permanent forest dynamics plots (FDPs). We describe the digital data collection methods we developed for the first census; we anticipate efficiency and time savings to increase with each re-census. We then compared data collection and data entry time estimates in this case study with those for other FDPs that followed the same tree measurement protocols, but used written data collection methods. We calculated approximate savings realized from the implementation of digital methods. In addition, we analysed plot data to test for possible factors underlying the variation in data collection rates (i.e., tree density and number of species). The information presented here is broadly applicable to ecological research, especially when location data are recorded.

Materials and methods

PLOTS

In 2007–2009, the Hawaii Permanent Plot Network (HIPPNET) established two 4-ha plots on the Island of Hawaii at Laupahoehoe and Palamanui. The Laupahoehoe plot is located in mid-elevation wet forest and the Palamanui plot is located in low-elevation dry forest (http://www.hippnet.hawaii.edu). HIPPNET is part of a global network of 34 FDPs affiliated with the Smithsonian Tropical Research Institute, Center for Tropical Forest Science (CTFS; http://www.ctfs.si.edu, accessed on 14 January 2010). In each FDP, all trees ≥1-cm d.b.h. (i.e., at 1·3-m from tree base) are identified, permanently tagged and measured according to standard protocols developed for the first plot on Barro Colorado Island, Panama (BCI). In addition, each tree is mapped relative to a precisely installed grid system of 20 × 20-m quadrats. CTFS plot sizes range from 2-ha to 52-ha and have from 15 to 1182 species represented by 11 900 to 360 000 stems per plot. Plots are re-censused every 5 years. In all of the plots, trees are measured and mapped using standard protocols (Condit 1998). Most CTFS plots continue to use written data collection methods. To date, we are aware of only two locations, Hawaii and Wabikon Lake Forest in Wisconsin, that have adopted a digital system (Robert Howe, *pers. comm.*).

DESCRIPTION OF HIPPNET DATA COLLECTION METHODS

Hardware and software

Tree location and attribute data were collected data using ArcPad (version 7.0.1.53 copyright ©1995–2006; ESRI, Redlands, CA, USA) installed on Allegro field computers (Allegro CX, Juniper Systems Inc., Campbell Scientific, Utah, USA; cost = $1600–3000 per unit); Allegro field computers are currently used by the USDA Forest Service's Forest Inventory and Analysis Program to monitor permanent vegetation plots across the United States (http://fia.fs.fed.us/). These field computers are completely waterproof and shock-resistant, with data entry by alphabetic and numeric keypads and touch screens. The rechargeable battery lasts all day (10 h) and can be recharged in a vehicle as necessary. Data and programmes can be stored without battery power in the built-in flash memory drive and removable memory cards can be purchased. If data are saved into stable memory, the data should be extractable even if the field computer were to crash. Thus, as long as data files are backed up at the end of each field day, no more than 1 day of work would be lost due to system failure. The HIPPNET project has used three units continuously for 2 years and we expect them to be usable for several more years.

To create and edit maps on field computers, we used ArcPad, a simplified mobile version of ArcMap (ArcGIS Desktop 9·2 Copyright © 1999–2006; ESRI). Its functions are similar to ArcMap without many of the more advanced features. We used ArcPad Application Builder (v. 7·0·1·2OU Copyright © 2002–2006; ESRI) to create custom data collection forms for ArcPad. ArcPad data were downloaded/uploaded to/from PC's using Microsoft® Active-Sync® (v. 4·5·0 Copyright © 1996–2006; Microsoft Corporation, Seattle, WA, USA). On the PC, we used built-in ArcGIS tools to update data stored in ArcGIS geodatabases. Data can then be opened in data base format (including Microsoft® Office Access®, Copyright © 2007; Microsoft Corporation) to generate error reports and export to other formats for analysis.

Data flow

Create and export data collection files. Our data were stored within geodatabases to be easily exported to ArcPad for data collection and imported back to ArcMap for storage and analysis (Fig. S1, Supporting information, software templates and code available from authors upon request). Prior to data collection, an ArcMap geodatabase was created containing all the data collection fields. It was added to a GIS map along with additional layers as needed for reference. In our case, we added a grid-point layer we created to represent all the grid points in the plot and a polygon grid layer to represent each 20 × 20 quadrat. We exported our map in 20 × 20-m quadrat sections (about a day's work). To do this, we zoomed into the selected area and used the Export Data to ArcPad tool to create a new folder containing an ArcPad map referencing the map layers. Then, we copied our custom data collection form and any lists used by the form (e.g., species list for drop-down menu) into this ArcPad folder. In an additional step, we opened our form in ArcPad Application Builder and added the quadrat number to the 'quad' field as a default value to obviate repeatedly entering that value in the field. Finally, the ArcPad folders were uploaded to the field computer and taken to the field for data collection. Once the geodatabase, map layers, and custom forms were created, the entire data export process, including adding and editing form files, took less than an hour per hectare and could be done by assistants with only minimal instruction.

In-field data collection. In our plots, one crew member measured trees while another crew member entered the data into a field computer. To add a tree to the data set, the mapper opened the appropriate file for editing, zoomed into the correct location (usually the

5 × 5-m subquadrat) and tapped on the map to draw the tree at a location relative to the grid points on the map and on the ground. This action opened the custom data collection form in which tree identification, measurement and other attribute data were entered. Our data collection forms included drop-down menus for species names and notes, automatic date entry and required fields (e.g., must enter number ≥1 in tag field). We used one field-computer per mapping/measuring team and typically had 2–3 teams measuring at any one time.

Download data and update map data base. Following collection, data were copied from the field computer to a PC. We then used the 'Check in Data From ArcPad' tool in ArcMap to upload data to the map data base. This tool used a change-code generated in ArcPad to look for new and changed values and used this to update the geodatabase. The seamless integration of mapping and tree data collection removed the need to enter data and digitize maps from paper copies.

Methods comparisons among forest dynamics plots

We constructed a data-flow model to graphically illustrate and compare processes and potential sources of error for digital and written methods. This allowed clarification of the number of steps required by the different methods and identification of those steps in which errors were likely to be propagated.

We compared in-field data collection rates among FDPs in the CTFS network based on published rates and our own estimates from the Hawaii plots. In-field data collection rates for the initial census of six FDPs (BCI, Panama; Luquillo, Puerto Rico; Yasuni, Ecuador; Korup, Cameroon; Ituri, Dem. Rep. Congo) are available in Condit (1998) as trees per person per day; we did not include the Sri Lanka plot in our comparison of data collection rates as trees in that plot were identified and specimens were collected at the time of measurement, making their rate much slower and not comparable with the other plots, in which trees were identified separately. We calculated in-field data collection effort in person months per hectare by dividing the number of trees per plot by the product of the number of days worked per month and the number of trees measured per day over hectares per plot. To understand the variability in field data collection rate among FDPs (from 40 to 80 trees per day per person), we analysed the relationship between data collection rates and plot variables that may affect data collection rate, i.e., tree density (which varied from 3026 to 7200 trees/ha) and number of species (which varied from 35 to 1114 species) using ordinary linear regression (R language; *lm* function; R Development Core Team 2009).

To estimate the data entry effort from paper forms onto computers for plots other than BCI, we calculated the per tree data entry effort for BCI (28 person months for 208 400 trees = 0·000134 person months per tree; approximately 1·35 minutes per tree; Condit 1998, p. 98). We multiplied the BCI value by the number of trees per hectare in the given plot to determine the data entry effort in persion months per hectare. We estimated digital data entry rates (digitally uploading field computer data to a computer data base) from our own records.

We compared estimates of the total effort required for collecting field data manually, that is, writing tree locations and measurements on paper forms and then later manually entering the paper form data into a computer data base, with total effort for digital methods. Total effort required for data collection was calculated as the sum of in-field data collection plus data entry efforts. We also calculated data entry effort as a percent of total effort (data entry effort (person months plot^{-1})/total effort (person months plot^{-1}) × 100%).

Results

DATA FLOW MODEL

In a comparison of the data collection, entry and checking steps of digital and written methods (Fig. 1), we identified similarities and differences in the overall process and the potential sources of error. The first difference is the possibility of improved data quality during field data collection (*process 1*). In the field, data can be entered or written incorrectly or forgotten entirely for either method. However, with digital forms, it is possible to programme data validation to remind the user to enter data or check suspect values while in the field, potentially reducing overall error rates in the data. Second, and most importantly, digital data are uploaded from the field computer to a desktop computer instead of entered from paper data sheets thus saving effort and eliminating transcription errors (*process 2*). Our digital approach eliminates the need to re-check paper data sheets and to revise incorrectly entered data (*process 4*). The field error check step is similar for both methods except that digital, instead of printed, maps and data sheets may be used with digital methods (*process 5*). Finally, corrected values from field checks are entered by hand for paper methods while for digital methods they are uploaded and the data base may be automatically updated (*process 6*).

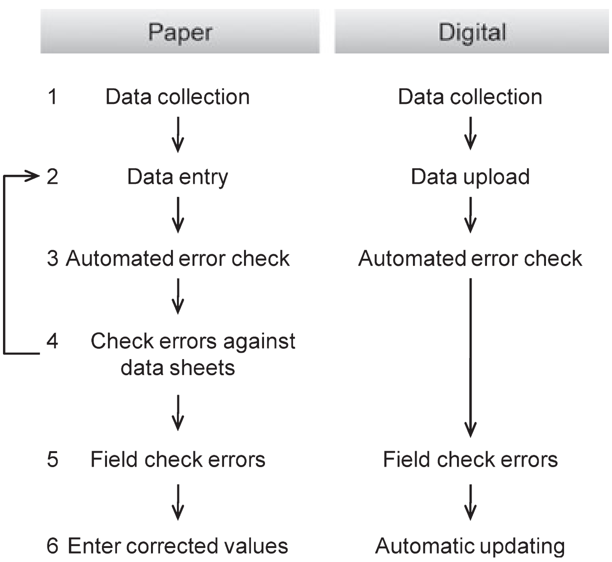

Fig. 1. Data flow models for paper and digital data collection, entry and checking processes; numbers indicate steps in the data collection and entry process (*process 1*: in-field data collection with overall effort similar between methods but errors possibly reduced in digital method due to data validation; *process 2*: data are entered manually for written methods and data are uploaded for digital methods, transcription errors may occur with written method; *process 3*: automated error checks occur once the data are in the data base similarly for both methods; *process 4*: errors are checked against paper data sheets for paper but not digital methods; *process 5*: field error checks are similar except that digital maps and data sheets may be used with digital methods; *process 6*: for paper methods, corrected values from field checks are entered by hand and for digital methods, they are uploaded and the data base is automatically updated).

METHODS COMPARISONS AMONG FOREST DYNAMICS PLOTS

In our analysis of data collection rates and tree density and species per plot, we found that tree data collection rate was independent of the number of species represented in a plot ($r^2 = 0{\cdot}05$; $P = 0{\cdot}66$) but increased with stem density ($r^2 = 0{\cdot}79$; $P = 0{\cdot}017$). Given the high variation in number of trees per hectare and number of species, the data collection effort in person months per hectare was relatively conservative across sites, ranging from 2·8 person months ha^{-1} for Yasuni to 5·1 person months ha^{-1} for Korup (Fig. 2). Hawaii's value (4·6 person months ha^{-1}) fell close to the average for all the other five plots (4·2 person months ha^{-1}).

As expected, the estimated data entry effort for digital methods was much less than for written methods (Fig. 2), resulting in a significant reduction in total effort. Data entry constituted an average of 12% (±SE 0·5%) of total effort for plots using written methods; for digital methods in Hawaii, it was 0·2%.

Discussion

We found that the implemention of digital data collection methods in forest plots was practical and resulted in high efficiency. Comparison with estimates for the global network of CTFS plots shows a reduction in data entry effort resulting from use of digital methods and potentially a lower total effort. In all plots using written methods, data entry effort is a substantial proportion of the total effort; the minimized data entry time for digital methods would result in an 11·8% average reduction of total effort. Thus, eliminating data entry time would enable savings of 9–35 person months per census depending on the size of the plot (mean = 25 person months). Such a saving in human effort translates into a savings of $18 000–$70 000 USD (mean $50 000), assuming an average salary of $2000 per month for data entry personnel. We note that salaries can be widely different, and the cost-savings may also vary across plots, but would be expected to always be important given that data entry from paper forms was always a substantial percent of total effort when using manual methods. Thus, even for small plots, the savings in effort of using digital data collection would more than compensate for the expense of field computers and software. This is important because forest dynamics data are proving essential for understanding ecological processes and an increasing number of FDPs are currently being developed. The ability to maximize limited resources can therefore increase the potential to further expand research agendas.

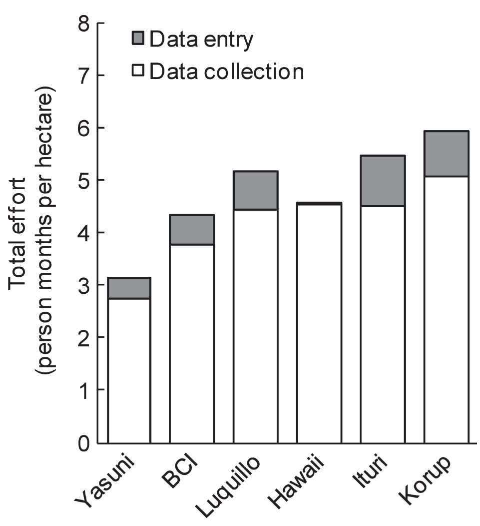

Fig. 2. Total effort in person months per hectare (data collection effort + data entry effort) for six Forest Dynamics Plots; data entry values for all plots except Hawaii based on published values (Condit 1998; http://www.ctfs.si.edu).

Based on our analysis of the variation of rates of in-field data collection among plots, the Hawaii rate is about what is expected for a plot with our tree density, suggesting that our digital data collection methods did not have a strong effect on field data collection rate. Instead, the field data collection effort (person months ha^{-1}) for Hawaii plots was close to the average for other plots we examined. Although digital methods allow features such as default values and drop-down menus that may presumably increase the speed of data collection, we found no savings in data collection time in Hawaii as compared with other CTFS plots. This may be because the digital data collection features that may speed up data collection are compensated by the necessity of collecting data for only one tree at a time per measurement crew. Interestingly, across FDPs the per tree data collection rate increased with tree density, presumably because of the more limited travelling time between trees when they are closely spaced; this relationship explains the relatively conservative (less than twofold) range in field data collection effort across plots despite the wide range of species diversity and tree density among plots. Indeed, we had expected that plots with high species diversity might have slower data collection rates, but that was not the case, probably because most plots do not identify species when they are measured. Although in Hawaii we did identify trees while mapping and measuring, we did not collect specimens, so this probably did not strongly affect our data collection rate.

Understanding the effects of digital methods on in-field data collection rate is important because the majority of effort is in the field; if digital methods made data collection slower, then the time savings of data entry may be negated. Our finding of similar in-field data collection effort is subject to uncertainty because we compared across multiple plot projects; a clearer estimate would require comparing paper and digital methods using both methods within a given plot which is outside the scope of this case study. However, beyond the question of in-field data collection, based on the data flow model comparing of paper and digital methods, it is clear that digital data collection methods could drastically reduce data entry time and eliminate transcription errors. In addition, the fewer steps required for digital data collection can make these systems easier to manage. Further, because there are no data entry errors caused by transcription from paper to digital, it is not necessary to recheck the paper forms, thereby also saving time in data checking. An additional advantage is that measurements can be immediately uploaded and analysed thereby increasing the ability to rapidly compare and standardize data across plots.

Digital data collection methods have additional advantages for collection of spatially explicit field data. The seamless integration of mapping and data collection removes the need to enter data and digitize maps from paper copies. Instead, data collected on field computers can be automatically incorporated into the main data base from the field copies. Lists of errors, such as suspect and missing values, can be quickly generated along with maps to locate problem trees. Finally, our field crews typically found the Allegro field computers easy to use and simpler than switching between separate paper data sheets needed for mapping and recording data. Allegro field computers are ruggedized and waterproof and can be less problematic than paper data sheets in inclement weather. Our results are consistent with previous publications on digital data collection methods that found large increases in efficiency from the application of digital methods in other project designs (Waddle, Rice, & Percival 2003; van Tamelen 2004). Indeed, digital methods have been used extensively for the past several years to collect vegetation data (e.g., the Forest Inventory and Analysis Program of the U.S. Forest Service), and our study supports that practice, given the efficiency of digital methods as compared with that of paper-based methods.

POTENTIAL RESERVATIONS TO USING DIGITAL DATA COLLECTION

During the development and practice of our digital approach, and in numerous discussions with field ecologists, several concerns were raised pertaining to plots converting to a digital data collection approach. These are described and the ways in which potential problems might be addressed are listed below, with the clear proviso that further development of digital methods will likely increase efficiency and decrease costs for many similar large-scale projects.

The potential for system crashes that can result in losses of data is a primary concern for field ecologists. That problem can be minimized by: (i) saving files on stable drives that are not erased if the battery dies or the programme crashes; (ii) daily downloading of collected data; and (iii) regular backup to onsite and offsite storage. These precautions are simple, take just a few minutes per day, and should prevent the loss of more than a day of work – and this would be only if the system were to fail. Indeed, with regular offsite data storage, the risk of data loss due to catastrophic events may less than paper-based methods, because paper data collection methods are not immune to data loss (e.g., due to lost or damaged data sheets).

The cost of hardware and software is another major concern. These problems are especially acute for researchers in developing countries, graduate students with little funding, and small, short-term projects. For these projects, digital methods may still be useful given that less expensive hardware and software options are available, although not explored in this study. However, for larger projects, the savings in data entry time should more than compensate for the cost of equipment purchased, as described above.

We note that there may be a large initial time investment to set up a new system and create customized forms. Of course, to create a well-designed paper datasheet also takes time. We have found that simple digital forms made in spreadsheet programmes can actually be much faster and easier to create than paper forms given that fields can be created or edited in the field as needed. Using off-the-shelf instead of custom programmes also saves time and makes it easier to adapt methods to other projects. These programmes are typically user-friendly and do not require programming skills, and allow modifications to ensure high quality data collection.

The need for electricity may be a drawback to using digital methods in situations where it might not be available in remote field sites. The battery in the Allegro field computer lasts about 16 h and can be charged using a vehicle outlet, but greater difficulty may arise for plots sited far from any roads. Field computers can lose their charge in the middle of a field day if not charged properly. In this case, back-up datasheets or a plan for another activity will ensure that the time spent travelling to and from the field site is not wasted.

The small screen size of the Allegro may make some types of data collection awkward. However, in ArcPad, it is possible to zoom in or out to any scale to see larger or smaller areas. For example, it is possible to zoom in and see closely spaced trees that may be hard to visualize on paper forms.

These principal reservations can thus likely be overcome and digital collection systems can be further improved by implementing several principles. Most importantly, it is ideal to create data collection forms to work with the natural flow of data collection and the preferences of the field crew. It is easier to adjust the system to work with the people than trying to adjust the people to the system. Fine-tuning the system to work with the natural flow of data collection will add speed and probably result in fewer errors. For example, in our plots, the crew first read the tag number, so in the data entry form this field comes first. Then, the person collecting data can tab through each field in the order they are customarily measured in the field. Developing a system that works smoothly with the field crew requires that the project manager solicit and implement feedback from the field crew on a regular basis.

The findings of our case study pointed to substantial efficiency of digital methods that should be applicable to many other studies and opens up further questions for study. Further research should quantify the difference in in-field data collection accuracy between digital and paper methods given that these methods allow the incorporation of pre-set default field values, required fields, automated in-field data checking and drop-down menus. These comparisons would be valuable for evaluating the utility of digital methods. Further estimation of savings in data entry would also be beneficial. Finally, we note that it is important for plot managers to carefully evaluate all options to choose the system that best fits their needs and available resources. We hope this article will aid in that evaluation process.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. HIPPNET data flow process: data from ArcMap are exported to ArcPad, data are collected on custom forms, then data are imported to the map and the underlying geodatabase is automatically updated.

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