Environ Monit Assess (2011) 179:123–135
DOI 10.1007/s10661-010-1723-x

Patch size and shape influence the accuracy of mapping small habitat patches with a global positioning system

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Received: 21 January 2010 / Accepted: 20 September 2010 / Published online: 2 October 2010

Abstract Global positioning systems (GPS) are increasingly being used for habitat mapping because they provide spatially referenced data that can be used to characterize habitat structure across the landscape and document habitat change over time. We evaluated the accuracy of using a GPS for determining the size and location of habitat patches in a riverine environment. We simulated error attributable to a mapping-grade GPS receiver capable of achieving sub-meter accuracy onto discrete macrophyte bed and wood habitat patches (2 to 177 m^2) that were digitized from an aerial photograph of the Laramie River, Wyoming, USA in a way that emulated field mapping. Patches with simulated error were compared to the original digitized patches. The accuracy in measuring habitat patches was affected most by patch size and less by patch shape and complexity. Perimeter length was consistently overestimated but was less biased for large, elongate patches with complex shapes. Patch area was slightly overestimated for small patches but was unbiased for large patches. Precision of area estimates was highest for large (>100 m^2), elongate patches. Percent spatial overlap, a measure of the spatial accuracy of patch location, was low and variable for the smallest patches (2 to 5 m^2). Mean percent spatial overlap was not related to patch shape but the precision of overlap was lower for small, elongate, and complex patches. Mapping habitat patches with a mapping-grade GPS can yield useful data, but research objectives will determine the acceptable amount of error and the smallest habitats that can be reliably measured.

Keywords Habitat mapping · Habitat patches · Global positioning system · GPS · Geographic information system · GIS · Simulation · Error · Root mean squared error · Trimble

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Introduction

Measuring the size, shape, spatial position, and temporal change of habitat patches used by animals is important to understanding how habitats influence individuals and populations (Knutson et al. 1999; Kocik and Ferreri 1998; Linke et al. 2005; Schlosser and Angermeier 1995). There are many field methods for measuring aquatic (Bain and Stevenson 1999) and terrestrial (Braun 2005) habitats, but most lack the ability to provide a spatial framework for habitat conditions. A spatial framework allows researchers to investigate how the juxtaposition and connectivity among habitat patches influences the distribution and abundance of organisms (Knutson et al. 1999). Large quantities of georeferenced data can be collected using remote sensing techniques, and these data are often available from the Internet. However, the relatively large grain size (i.e., low spatial resolution) of such data limits its usefulness for studying habitat patchiness at the spatial scales that may be important for many small-bodied organisms. Also, remotely sensed habitat data can have high levels of misclassification error (20.4% misclassification of land cover; Wyoming Gap Analysis 1996) and can be expensive to obtain for site-specific projects (Allen 1994; Fisher 2004). Therefore, biologists often resort to collecting spatially-referenced habitat data in the field and the most common way to do this is by using a global positioning system (GPS).

Global positioning systems are increasingly being used to collect spatial data for environmental research and management (August et al. 1994; Johnson and Barton 2004). For example, GPS has been used to map freshwater habitats (Jeffrey and Edds 1997; O'Connor and Rahel 2009; Valley et al. 2005), marine habitats (Smith and Greenhawk 1998), terrestrial wildlife habitats (Hulbert and French 2001), and terrestrial vegetation patches (Webster and Cardina 1997). Once habitat patches are mapped using GPS, their size, geographic location, proximity to other habitat patches, and change in size and location over time can be measured in a geographic information system (GIS; Baxter 2002; Dauwalter et al. 2006; Le Pichon et al. 2006; Torgersen et al. 2004; Webster and Cardina 1997). In general, the size of habitat patches mapped in most studies is relatively large (>100 m^2) compared to the size of habitat patches such as macrophtye beds and wood accumulations that are important to small-bodied organisms such as stream fishes (Belica and Rahel 2008; Le Pichon et al. 2009). Thus, there is a need to evaluate the accuracy of habitat patches with a GPS at small spatial scales.

The accuracy of a GPS determines whether it can be used to reliably map habitat because mapping errors can result in false conclusions regarding habitat characteristics, habitat change, and species–habitat relationships (Visscher 2006). The accuracy of GPS locations is typically expressed as a measure of precision. Precision is referenced as a root mean squared error (σ_{error}) that is the product of the two independent errors, pseudorange error, also known as user equivalent range error (σ_{UERE}), and dilution of precision (DOP). Pseudorange error is composed of several sources of error that affect the satellite-to-user range measurement; that is, the estimated distance between a satellite and a GPS receiver used to estimate location (discussed in Conley et al. 2006). Pseudorange error is approximated as a zero mean Gaussian random variable, $N(0, \sigma_{\text{UERE}})$ (Conley et al. 2006). Dilution of precision is unitless and expresses the composite effect of user-satellite geometry and GPS receiver satellite-selection algorithm (i.e., the satellites selected by the receiver to compute location) on the error in locations estimated using GPS; positional dilution of precision (PDOP) is most commonly used and expresses the effect of satellite geometry on horizontal and vertical precision. If DOP can be assumed fixed because GPS locations are collected over small areas and short time periods, then $\sigma_{\text{error}} = \text{DOP} \times \sigma_{\text{UERE}}$ where DOP is known for that location and time. If GPS locations are determined over larger areas and longer time periods then DOP is a random variable and $\sigma_{\text{error}} = \text{DOP}_{\text{rms}} \times \sigma_{\text{uere}}$ where DOP_{rms} is the root mean square of DOP computed as cumulative density function of discrete DOP values (Leva et al. 1996). Regardless of how σ_{error} is computed, two-dimensional error is referenced as horizontal root mean squared error ($\sigma_{\text{h-error}}$) that results from the variance of errors along the x and y axes: $\sigma_{\text{h-error}} = \sqrt{\sigma_x^2 + \sigma_y^2}$. The probability that a GPS location is within a circle having a radius of 1 σ_{error} is 0.63 for a circular error distribution and 0.69 for an elongated distribution. For 2 σ_{error}, probabilities are from 0.95 to 0.98 depending on the circularity of the error distribution (Conley et al. 2006).

Our objective was to determine how horizontal GPS error ($\sigma_{\text{h-error}}$) influences the characterization of discrete two-dimensional habitat patches and the detection of habitat change over time when habitats are mapped using GPS. To meet this objective we quantified the error associated with mapping aquatic habitat patches using GPS in the Laramie River, a high plains stream in southeastern Wyoming, USA. We explored how the amount of error was related to habitat size and shape. We focused on discrete patches consisting of macrophyte beds or wood accumulations that are important to fishes in riverine habitats (Belica and Rahel 2008; O'Connor and Rahel 2009). Determining how GPS error affects measurement of discrete two-dimensional habitats will help to identify the size and shape of habitats that can be reliably measured, and the magnitude of habitat change that can be detected, when habitats are mapped with a GPS. Although we evaluate the effect of GPS error in the context of mapping riverine habitats, our results are applicable to any two-dimensional discrete habitats that are measured and mapped using GPS under similar environmental conditions.

Methods

Habitat patches

We evaluated the error in mapping habitat patches with GPS by simulating horizontal GPS error onto discrete macrophyte bed and wood patches that were digitized from an aerial photograph of the Laramie River, Albany County, Wyoming, USA (Fig. 1). An aerial photograph of a 2-km segment of the Laramie River was taken after leaf-off in autumn 2003 and then ortho-rectified (Horizons Inc., Rapid City, South Dakota, USA). This segment of the Laramie River is a high plains stream with some riparian areas with trees and shrubs (*Salix* spp.) and other areas dominated by herbs and grasses. The aerial photograph had a 0.1-m pixel resolution with 90% of all features accurate to 0.042 m and the remaining features accurate to 0.084 m. All 97 macrophyte and wood habitat patches >2 m^2 within the

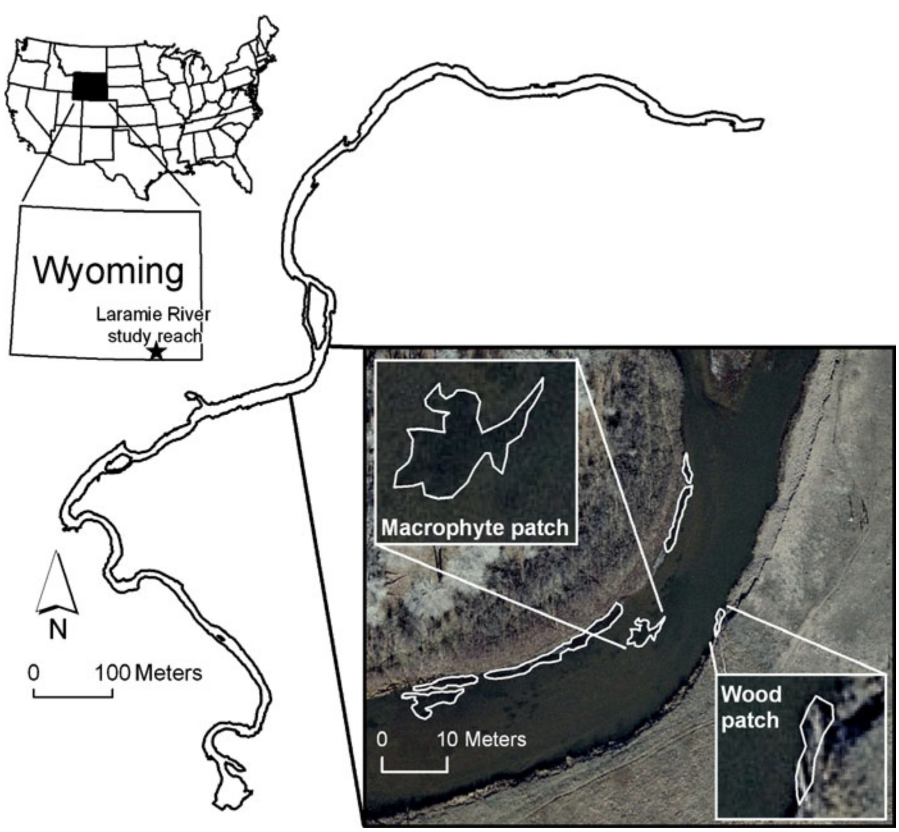

Fig. 1 The 2-km study segment of the Laramie River, Wyoming, USA where habitat patches were digitized from an aerial photo to evaluate the effects of GPS error on measuring habitat patches. *Insert* shows an example of a macrophyte patch and a wood patch that were digitized from the aerial photo

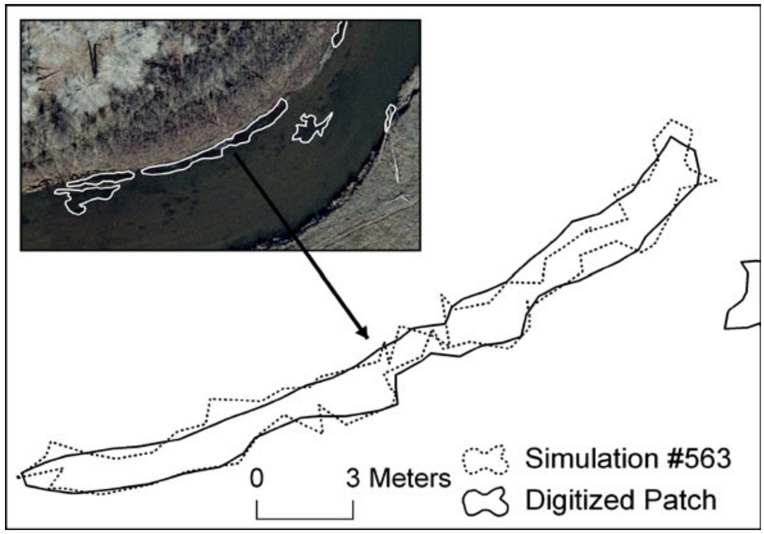

Fig. 2 An example of a simulation where GPS error was added onto a digitized macrophyte patch in the Laramie River, Wyoming, USA. The original patch is shown by the *solid outline*, and the simulated patch with error is shown by the *dotted outline*

2-km segment of the Laramie River were digitized as polygons in the GIS software ArcGIS 9.2 (ESRI, Redlands, CA). Digitizing was done in a way that simulated on the ground mapping with a GPS receiver: patches were digitized as polygons, and polygon vertices were placed every 0.5 m along the margin of each habitat patch. This procedure has been used previously during GPS mapping of Laramie River habitat patches (O'Connor and Rahel 2009).

Digitized patches included a range of sizes and shapes. We also digitized simulated patches consisting of squares, rectangles, or crosses to determine how GPS error was related to patch size and shape. Digitized habitat patches were characterized using three metrics: area, elongation, and complexity. Area was used to characterize habitat patch size. Elongation was measured as: *Area*/*Length*^{2}, where length is measured along the longest axis. Elongation ranges from near 0 for very elongate shapes to 1 for a square and is commonly used to quantify watershed morphology (Gallagher 1999a). Shape complexity was measured as the perimeter-to-area ratio: *Perimeter*/$(2 \cdot (Area \cdot \pi))^{0.5}$. This ratio ranges from 1 for a perfect circle to >1 for complex shapes that have much longer perimeters per unit area and is often referred to as the shoreline development index (Gallagher 1999b). Area, elongation, and complexity of digitized patches were measured using ArcGIS 9.2. All GIS files were displayed and analyzed in the Universal Transverse Mercator, Zone 13 coordinate system, and WGS84 datum.

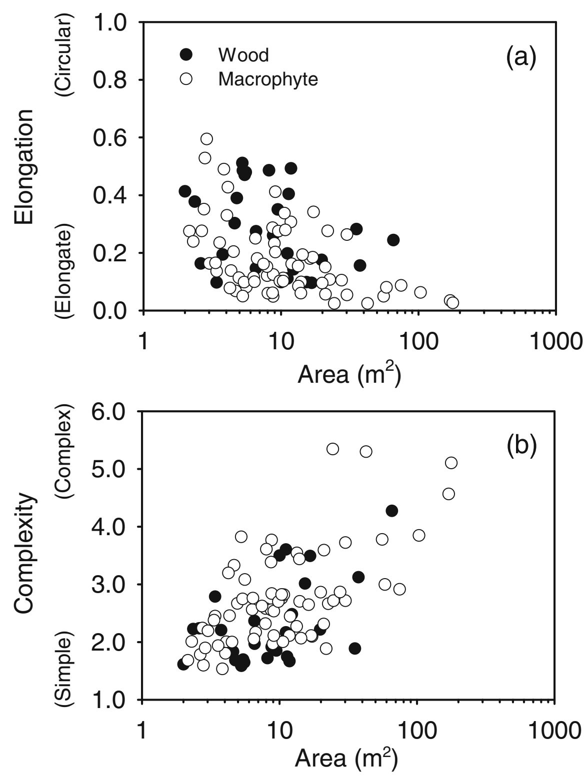

Fig. 3 Relationships among area, elongation, and shape complexity for macrophyte and wood patches in the Laramie River, Wyoming, USA

Simulating GPS error

Using the digitized habitat patches, we simulated horizontal GPS error ($\sigma_{\text{h-error}}$) onto each polygon vertex of a digitized patch to simulate the effects of GPS error on habitat patches mapped in the field. We simulated error associated with the Trimble ProXRS GPS receiver (Trimble Navigation Limited, Sunnyvale, CA, USA) that is commonly used to measure aquatic and terrestrial habitats (Belica and Rahel 2008; Schilling and Wolter 2000; Webster and Cardina 1997). The ProXRS receiver has a horizontal root mean square of 0.5-m ($\sigma_{\text{h-error}} = \sqrt{\frac{1}{N}(\sum_{i=1}^{N}(h_i)^2)} = 0.5$ m; where N = number of position observations in dataset and h_{i} = horizontal error of ith observation) when code phase signals are used for satellite range measurements and data are differentially corrected (see Cosentino et al. 2006) and collected under the following conditions: minimum of four satellites; maximum PDOP of six, minimum signal-to-noise ratio of 39 dBHz, minimum satellite elevation of 15°, and reasonable atmospheric and multipath conditions (Datasheet: GPS Pathfinder Pro XRS receiver; Trimble Navigation LTD, Westminster, CO). These conditions are meant to represent ideal environmental conditions for collecting GPS data, are commonly used to control the quality of GPS data during data collection and post-processing, and are set as quality-control defaults in the ProXRS receiver. The GPS receiver will not allow data to be collected when these conditions are not met. The manufacturer-specified horizontal root mean square is determined by collecting GPS data at approximately a 5-s interval for several hours (up to 24 h) at a known location, comparing the error in GPS determined positions to the known position, and summarizing the distribution of known errors as the horizontal root mean square of errors (Trimble Navigation Limited 1997). GPS error was added onto the x and y coordinates of each polygon vertex by randomly selecting error for

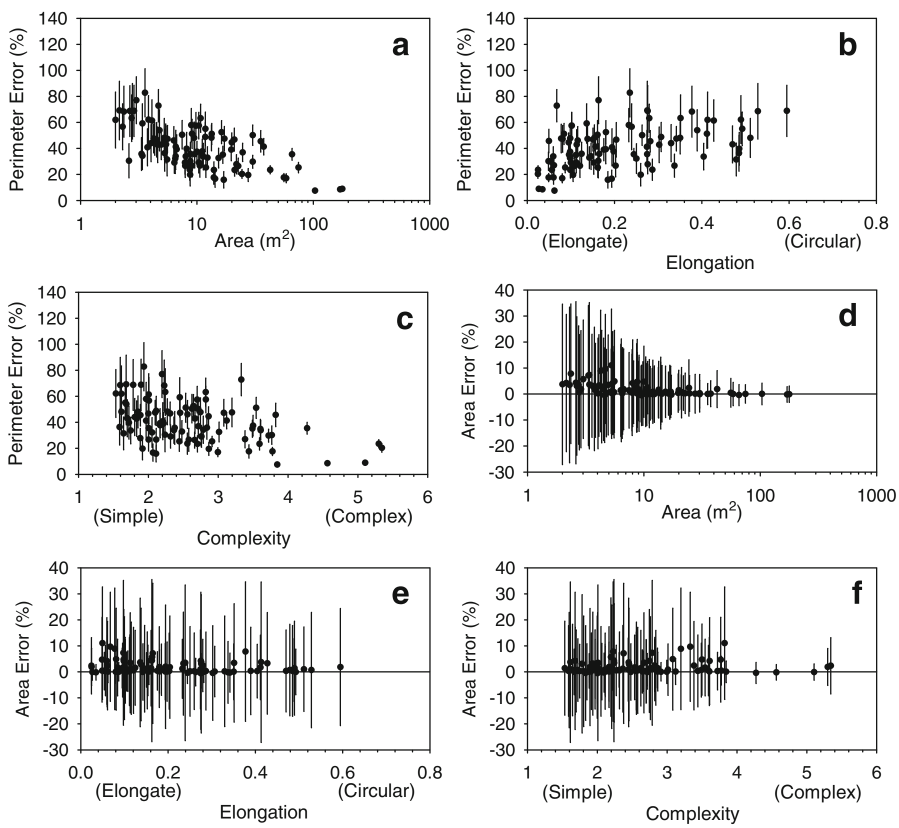

Fig. 4 Percent error in perimeter length and area of habitat patches in relation to patch area, elongation, and shape complexity after GPS error was simulated for digitized wood and macrophytes patches. *Circles* represent the mean and *error bars* represent 1 SD of 1,000 simulations per patch

each coordinate from a Gaussian distribution. The distribution for each coordinate was specified using the relation $\sigma_{\text{h-error}} = \sqrt{\sigma_x^2 + \sigma_y^2}$, where $\sigma_x^2 = \sigma_y^2$. Since $\sigma_{\text{h-error}} = 0.5$ m for the ProXRS receiver, $\sigma_x = \sigma_y \approx 0.3535$ m. Thus, the simulated error on the x- and y-axes was drawn from a normal distribution with a mean of 0 and a SD of 0.3535 m. Coordinates of vertices were exported into SAS, Version 9.3 (SAS Institute Inc, Cary, NC) and error was simulated onto each vertex of all 97 patches 1,000 times. After error was simulated onto each vertex, the 1,000 replicated polygons per patch were reconstructed in ArcGIS 9.2 and patch characteristics were measured (Fig. 2).

We quantified GPS error in mapping habitats by comparing each simulated patch to the original digitized patch. For each simulation, we computed the percent error in perimeter as: $[(\text{Perimeter}_{\text{simulated}} - \text{Perimeter}_{\text{original}}) / \text{Perimeter}_{\text{original}}] \times 100$, and percent error in area as: $[(\text{Area}_{\text{simulated}} - \text{Area}_{\text{original}}) / \text{Area}_{\text{original}}] \times 100$. The effect of error on documenting habitat change was determined by comparing the percent areal overlap between each simulated patch and the original digitized patch: $[\text{Area}_{\text{overlap}} / \text{Area}_{\text{original}}] \times 100$. The amount of error in perimeter, area, and overlap was compared to patch area, elongation, and complexity to determine how those factors influenced the amount of error observed when mapping habitat patches with a mapping-grade GPS.

We used a statistical power analysis to determine how horizontal GPS error might influence detection of changes in patch size. We estimated the power to detect 5% to 100% changes in size for patches ranging from 2 to 200 m^2. We used a Type I error rate of 5% (two-tailed $\alpha = 0.05$). For the analysis, we specified that variances were proportional to patch area (based on our simulated data; variance/mean = 0.16) and sample size was $n = 2$. A sample size of $n = 2$ was used because we were interested in the ability to detect changes in patch size when measuring a patch with a GPS receiver only once during an initial time

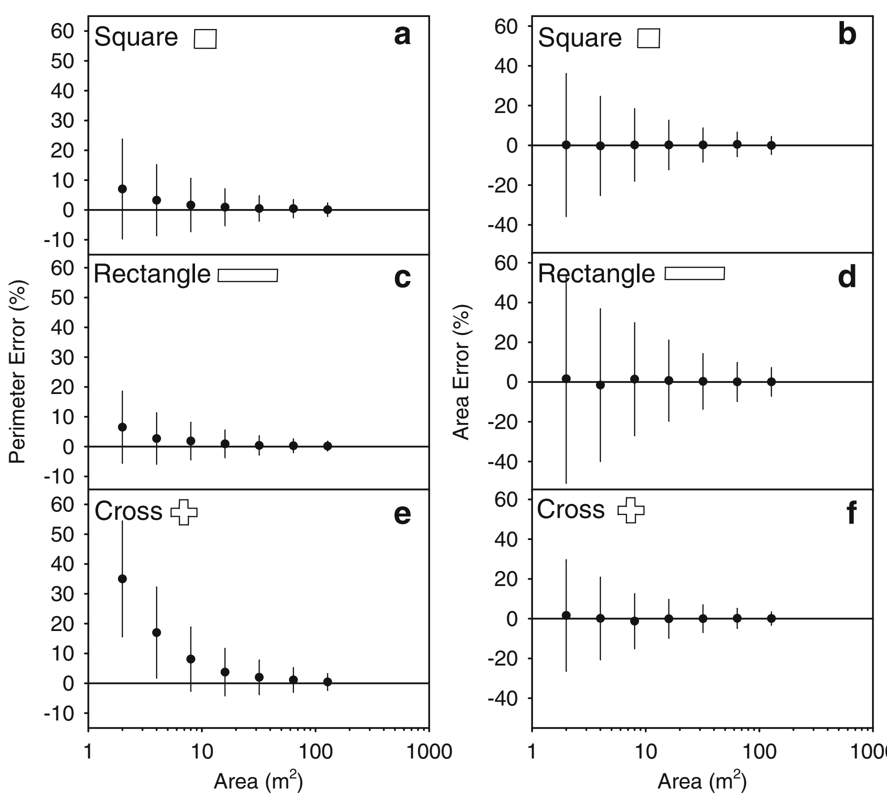

Fig. 5 Percent error in perimeter length and area of known shapes of different sizes. The *rectangle* had a 5:1 length to width ratio (elongation = 0.2). All perimeter line segments of the cross were equal length. *Circles* represent the mean and *error bars* represent 1 SD of 1,000 simulations per patch

period and once again at a later date. The analysis was conducted using an Excel tool developed by Gerow (2007).

Results

The shape of habitat patches in the Laramie River changed with patch area. Small patches were highly variable and ranged in shape from round to elongate whereas large patches tended to be elongate (Fig. 3a). Patch complexity was higher for large, elongate patches (Fig. 3b). These relationships were similar for both macrophyte and wood habitat patches.

Simulation of GPS error resulted in patch perimeters being consistently overestimated although the magnitude of error decreased with increasing patch area (Fig. 4a). The average error in perimeter estimates for small patches 2 to 5 m^2 ranged from 31% to 83% but the average error decreased to less than 10% for large patches >100 m^2 (Fig. 4a). The tendency to overestimate perimeter length was variable but decreased for elongate patches (Fig. 4b) and for patches with complex shapes (Fig. 4c). Overall, perimeter was more precisely estimated for large, elongate, and complex patches (Fig. 4a–c).

The area of large patches was more precisely estimated than the area of small patches and there was a tendency for the area of small patches to be slightly overestimated (Fig. 4d). The average error for measurements of patch area ranged from −0.4% to 9.7% among all simulations for the smallest patches (2 to 5 m^2) and from −0.2% to 0.0% for the largest patches (>100 m^2). Precision did not change with patch elongation (Fig. 4e). Precision was not related to patch complexity except for the most complex patches (which also were large; >100 m^2) where area was precisely and accurately estimated (Fig. 4f).

When GPS error was simulated onto known shapes, perimeter was overestimated for all shapes but was most biased for the complex cross shape that had the highest perimeter/area ratio (Fig. 5a, c, e). There was no bias in area estimates (Fig. 5b, d, f). The precision of perimeter and area estimates increased with patch area for all shapes as evidenced by the decline in SD (Fig. 5). Perimeter was estimated more precisely for the elongate rectangle than for the complex cross that contained more vertices (Fig. 5c, e). In contrast, area was estimated more precisely for complex cross shapes versus the square or elongate rectangle (Fig. 5b, d, f).

Percent overlap between digitized patches and patches with simulated GPS error increased and became more precise as patch size increased (Fig. 6a). Overlap averaged from 59% to 79% for the smallest patches (2 to 5 m^2) and averaged from 89% to 90% for the largest patches (>100 m^2). There were no apparent trends in percent overlap with patch elongation or complexity (Fig. 6b, c).

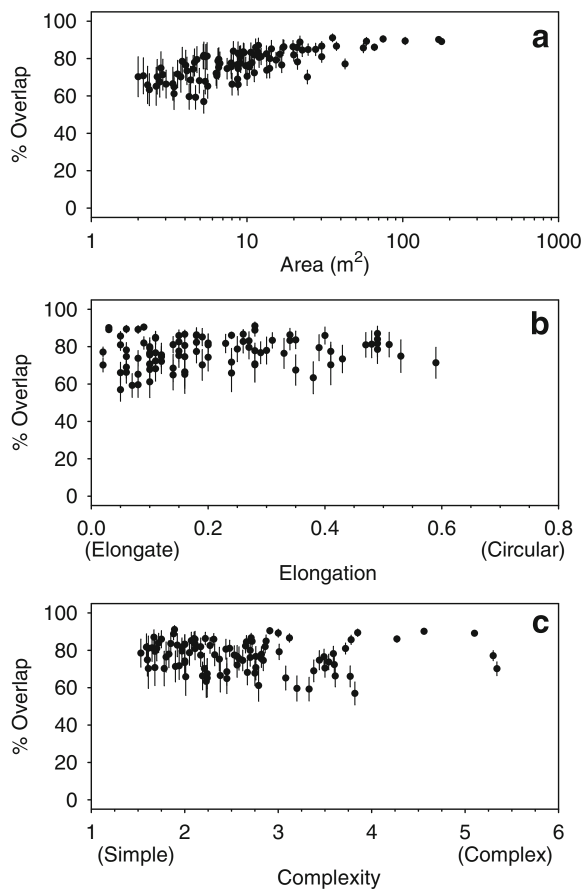

Fig. 6 Percent overlap in area of habitat patches with simulated GPS error and original digitized patch plotted against patch area, elongation, and shape complexity. *Circles* represent the mean and *error bars* represent 1 SD of 1,000 simulations per patch

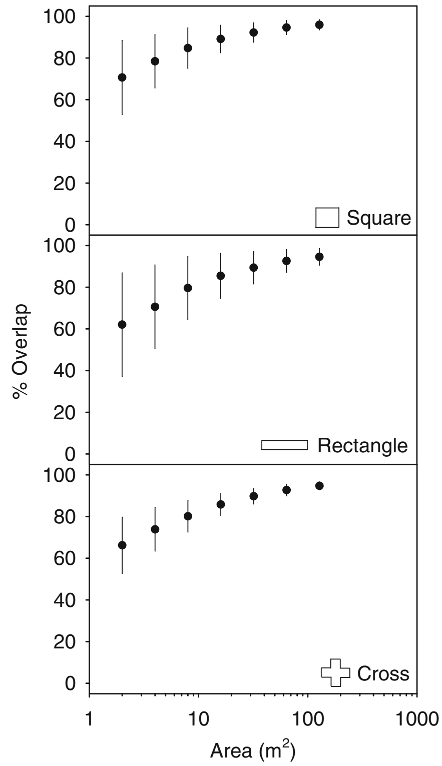

Fig. 7 Percent overlap in area between known shapes and the shapes with simulated GPS error as a function of shape area. The *rectangle* had a 5:1 length to width ratio (elongation = 0.2). All perimeter line segments of the cross were equal length. *Circles* represent the mean and *error bars* represent 1 SD of 1,000 simulations per patch

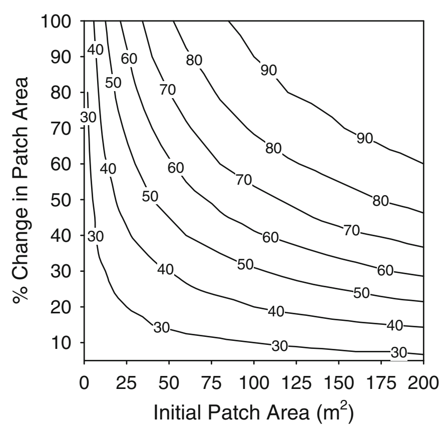

Fig. 8 Isopleths of statistical power, expressed as a percentage, to detect changes in patch size for varying patch areas. Power was computed assuming variances were proportional to patch area (based on our simulated data; variance/mean = 0.16), sample size was $n = 2$, and $\alpha = 0.05$

However, the precision of overlap was higher in large, elongate and complex patches (Fig. 6a–c).

Percent spatial overlap in known shapes with simulated GPS error increased with shape area and was slightly higher on average for the simple, symmetrical square versus the elongate rectangle and the complex cross (Fig. 7). For shapes with the same area, the precision in overlap was lowest for the elongate rectangle and highest for the complex cross and increased for all shapes as size increased (Fig. 7).

Given the error observed in GPS-measured patch sizes, the ability to detect changes in patch size increased with patch area (Fig. 8). There was low power to detect changes of even 100% in patches less than ~25 m^2. However, moderate changes (60%) in patches >50 m^2 and low-to-moderate changes (40%) to patches >100 m^2 could be detected with good power (>0.60).

Discussion

Our results indicate that the error in measuring the perimeter, area, and spatial location of habitat patches with a GPS depends largely upon patch area and to a lesser degree on patch shape. In most circumstances GPS can be used effectively to measure habitat patches greater than 50 m^2 regardless of their shape. However, when habitat patches are less than 50 m^2, researchers must carefully consider the patch sizes and shapes they intend to measure against their research objectives in order to determine whether GPS can be used effectively.

The precision in mapping habitat patches will depend upon the accuracy of the GPS receiver. Consumer-grade receivers are least expensive and have up to 19 m of error, mapping-grade receivers including the Trimble ProXRS that we used have 0.5 to 1 m of error, and survey-grade receivers have 0.1 m of error or less (Table 1). Although survey-grade receivers have the best precision, they are expensive, require setup of a nearby base station, and require greater user sophistication. Thus, many natural resource applications involve the use of mapping-grade receivers to inventory habitat conditions at spatial scales smaller than those that can be mapped by remote-sensing

Table 1 Manufacturer specified $\sigma_{\text{h-error}}$, observed $\sigma_{\text{h-error}}$, and mean horizontal error of consumer, mapping, and survey-grade GPS receivers reported from field studies

Receiver	Manufacturer-specified $\sigma_{\text{h-error}}$	Observed $\sigma_{\text{h-error}}$ [a]	Mean error (SD)	Source
Consumer-grade				
Garmin V	4.6	11.3	8.9 (6.9)	(Wing and Karsky 2006)
		2.8	2.6 (0.9)	(Wing et al. 2005)
Garmin Etrex Vista	4.6	2.4	2.2 (1.0)	(Wing et al. 2005)
Garmin Geko 301	4.6	4.7	4.2 (2.0)	(Wing et al. 2005)
Garmin GPSmap 76S	4.6	1.5	1.4 (0.6)	(Wing et al. 2005)
		11.8	9.8 (6.6)	(Bolstad et al. 2005)[b]
Magellan Meridian Platinum	3.5	20.0	19.6 (3.8)	(Wing et al. 2005)
Magellan SportTrak Map	3.5	1.9	1.8 (0.6)	(Wing et al. 2005)
Mapping-grade				
Trimble ProXR, XRS, XL	0.5	4.8	4.0 (2.8)	(Liu 2002)[b]
		0.5	NA	(Sigrist et al. 1999)
Trimble GeoXT	<1	0.6	0.5 (0.3)	(Wing et al. 2008)
		0.9	0.6 (0.6)	(Dauwalter et al. 2006)
		2.1	1.6 (1.4)	(Bolstad et al. 2005)[b]
Leica GS20	0.3	1.0	0.9 (0.4)	(Wing and Karsky 2006)
GENEQ SXBlue	0.3	8.8	7.8 (4.0)	(Wing and Eklund 2007)
Survey-grade				
Trimble System 5700	0.25	NA	0.02 (NA)	(Johnson and Barton 2004)

Precision and mean errors for mapping and survey-grade receivers are after differential correction. Data were collected under open-sky conditions unless otherwise noted. All units are meters
NA not available
[a] computed as: $\sigma_{\text{h-error}} = \sqrt{\text{SD}^2 + \text{Mean}^2}$ (from Naesset and Jonmeister 2002) if not reported directly
[b] Under forest canopy

techniques (Belica and Rahel 2008; Webster and Cardina 1997).

Precision of GPS data is also dependent on canopy cover (Naesset and Jonmeister 2002). Wing et al. (2008) found that horizontal errors from post-processed GPS data collected with a mapping grade receiver were not different between open-sky and young-forest (canopy closure 50%) conditions and only increased substantially in mature-forest (canopy closure nearly 100%) conditions. In addition, advancements in GPS technology continue to be made to reduce the effect of canopy cover on GPS data, and GPS receivers are often marketed as being effective in urban settings with challenging GPS environments. The Laramie River is a high plains stream and has an interspersed matrix of cottonwood gallery riparian areas against a background matrix of open riparian areas with grasses and sedges. The cottonwood gallery riparian areas never approached complete canopy closure. Majority of the study segment represented near ideal GPS mapping conditions because of the lack of complex terrain and little overhead canopy cover. Hence, our results are most likely to apply to similar physiographic regions as opposed to sites in mountainous terrain with dense forest canopy. The effect of GPS error on habitat patch characteristics in regions with complex topography and dense forest canopy should be an area of future research.

Given the widespread use of mapping-grade GPS receivers, what can be done to improve accuracy when mapping habitat patches? Most GPS receivers by default use code-phase signals to determine the distance between the GPS receiver and satellites. However, the use of carrier-phase signals can increase the precision of GPS receivers capable of using the signal, and the increase in precision is dependent on the length of time a remote base station collects data. For example, even the ProXRS can use carrier phase and decrease the $\sigma_{\text{h-error}}$ from 0.5 to 0.3 m after 5 min and to 0.1 m after 20 min (Trimble Navigation Limited

2005). However, use of carrier phase data requires a second receiver to serve as a remote base station and requires more setup time (Deckert and Bolstad 1996; Sigrist et al. 1999). It also requires an uninterrupted lock on satellite signals for the duration of mapping that can be difficult to obtain in some field conditions. This makes it unreliable without planning and a field trial. Use of code phase versus carrier phase signals is discussed by Cosentino et al. (2006) and Samama (2008).

Another option to increase precision is to collect more GPS data for a single location, such as a vertex along a patch boundary. Multiple position fixes can be averaged to estimate the spatial location of a single point or vertex on a polygon. However, Dauwalter et al. (2006) found no statistical difference in the accuracy of GPS points when 1, 10, or 100 position fixes collected at 1-s intervals were averaged to estimate locations. Wing and Karsky (2006) also found no improvement in accuracy when using 1 to 60 position fixes to compute spatial location. GPS data needs to be collected for several minutes before an appreciable gain in precision (e.g., 20% decrease in $\sigma_{\text{h-error}}$) is observed using multiple position fixes to compute location estimates (Naesset and Jonmeister 2002; Trimble Navigation Limited 1997). Collecting data for several minutes for each polygon vertex may not be feasible in most field mapping applications where one needs to collect multiple vertices for each patch and numerous patches need to be mapped. A more feasible option may be to map habitat patches multiple times and summarize the replicate patch measurements. In addition, if research questions are focused on the total area or patch composition in a study area then the GPS error will average out as long as the patch characteristics of interest are unbiased (e.g., area, but not perimeter).

Given the error associated with measuring small habitat patches with a GPS, certain metrics used to quantify habitat are more reliable than others. Proximity of habitats within a landscape can influence the ecology of some organisms (Matter 2006; Wiens 2002). Belica and Rahel (2008) mapped macrophyte bed and wood habitat patches in the Laramie River using GPS and found that inter-patch distance negatively influenced the rate at which creek chubs (*Semotilus atromaculatus*) moved between patches. Swihart et al. (2003) found non-volant mammals to occupy fewer patches in a landscape when patches were more isolated. The distance between patches should be the metric least affected by GPS error when GPS is used for measurements. Although we did not assess the error in distance between patch boundaries directly, the error of a line segment is largest at the vertices and smallest between two vertices (Leung et al. 2004). Therefore, the error in the distance between habitat patches is at most the error in spatial location of the two closest edges of two patches. This error is constant regardless of patch size and would average less than 1 m for mapping-grade receivers with a $\sigma_{\text{h-error}}$ of 0.5 m.

The error associated with measuring the area of habitat patches increased as patch size decreased and was considerable for small patches (2 to 5 m^2). Many questions in ecology require that the abundance of organisms be scaled to the availability of resources. Krauss et al. (2005) found that butterfly densities in Germany were related to the size of grassland patches and the quality and abundance of larval food plants. Accurate estimates of habitat area are required for densities to be measured accurately. Moreover, species–area relations are an important component of biodiversity studies (Angermeier and Schlosser 1989; Gleason 1922), and the area of habitats can influence colonization and extinction dynamics of habitats (MacArthur and Wilson 1967). When ecological questions are focused on small spatial scales that have small grains and extents (sensu Palmer and White 1994), accurate measurement of habitat area is essential. The error inherent in GPS data collected with mapping-grade receivers may, therefore, be of limited utility when ecological questions are focused on small habitat patches (2 to 5 m^2). However, small patches should not be ignored because they can support assemblages that can equal the richness and diversity of large patches (Hirst and Attrill 2008).

Boundaries of habitat patches mediate the exchange of individuals among different patches and can enhance biodiversity (Ries et al. 2004; Wiens 2002). Certain insects have higher densities near patch edges whereas others have higher densities away from edges, and the amount of edge per unit area can alter densities and diversity within a patch (Olson and Andow 2008). While perimeter length of habitat patches can be difficult to measure exactly because of its fractal dimension (e.g., how long is the coastline of Britian?; Mandelbrot 1967), ecologists define habitat patch perimeters at a resolution they perceive to influence their study organisms. The perimeters of habitat patches we identified in the Laramie River were highly variable and typically overestimated when they were measured with a GPS, and there was more bias in smaller habitats with complex shapes (i.e., higher perimeter/area ratio). Consequently, caution must be used when estimating the length of habitat boundaries and computing landscape metrics such as edge density of small patches. Overestimating the amount of patch boundary in a landscape mosaic can bias how edge effects are perceived to influence species movements and biodiversity across a landscape of small habitats. Biased estimates of edge length can also over accentuate the effects of human disturbances that increase landscape fragmentation (Bar Massada et al. 2008).

Habitats can be temporally dynamic. They change in size, shape, and connectivity (Hilderbrand et al. 1999; Remshardt and Fisher 2009). Baden et al. (2003) mapped eelgrass (*Zostera marina*) meadows along the Swedish coast and documented a decline in distribution for 50 of 69 meadows. Because eelgrass meadows were larger than 1 ha, the GPS error in their habitat maps was negligible. Dauwalter and Fisher (2008) mapped stream habitats over time using a mapping-grade GPS receiver and found that stream habitats shrunk and became disconnected during low-flow periods in late-summer and autumn. However, the reconnection of these habitats during high winter flows allowed smallmouth bass (*Micropterus dolomieu*) to access thermally unique winter habitats. The habitats used by smallmouth bass averaged 960 m^2 (range 10 to 4,092 m^2), and our results suggest that the accuracy in measuring the area of those habitats was high. Webster and Cardina (1997) evaluated the use of GPS to monitor the growth and invasion of a weed patch over time. They detected a 113% increase in the area of a hemp dogbane (*Apocynum cannabinum*) patch over 1 year. This patch was large enough (expanding from 116 to 241 m^2) that measurements of area should be relatively accurate and precise. Detecting meaningful habitat change over time requires knowledge of how much spatial overlap can be lost when measuring patches with a GPS.

Global positioning systems are increasingly being used to monitor aquatic and terrestrial habitats. If small, individual habitats less than 5 m^2 are of interest then detecting changes in size of individual patches will be difficult using a mapping-grade GPS receiver. Mapping such small patches may require a more accurate and precise survey-grade GPS receiver or traditional grid-based system that can be georeferenced (Matter 2006). For studies focused on large patches greater than 50 m^2 using a mapping-grade GPS receiver is probably acceptable and provides a useful technique for characterizing habitat conditions at spatial scales below those that require remote sensing. When habitat patches are between 5 to 50 m^2, researchers should carefully evaluate the errors associated with a mapping grade GPS receiver against their research objectives to determine if the GPS error will allow quantification of habitat patch characteristics at the desired level of accuracy or detection of sufficient levels of change over time. For example, given the level of GPS error we observed with the Trimble ProXRS, detecting a 40% increase in patch size with reasonable certainty (power of 60%) would be possible for a 100-m^2 patch but not a 25-m^2 patch. However, detecting 100% change in patch size would be possible for even 25 m^2 patches. Our results indicate that using a GPS to map habitat patches in streams is a viable tool for researchers and managers if care is taken to consider the effects of horizontal GPS error on the measurement of patch characteristics.

Acknowledgements S. Prager, J. Hammerlinck, A.J. Carlson, E.S. Hansen, K. Fesenmyer, and K.G. Gerow assisted with this research and provided helpful reviews of the manuscript.

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