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A database application for long-term ecological field experiments

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Abstract

Problem: A series of long-term field experiments is described, with particular reference to monitoring and quality control. This paper addresses problems in data-management of particular importance for long-term studies, including data manipulation, archiving, quality assessment, and flexible retrieval for analysis

Method: The problems were addressed using a purpose-built database system, using commercial software and running under Microsoft Windows.

Conclusion: The database system brings many advantages compared to available software, including significantly improved quality checking and access. The query system allows for easy access to data sets thus improving the efficiency of analysis. Quality assessments of the initial dataset demonstrated that the database system can also provide general insight into types and magnitudes of error in data-sets. Finally, the system can be generalised to include data from a number of different projects, thus simplifying data manipulation for meta-analysis.

Keywords: Data archive; Ecoinformatics; Ecological data; Ecological restoration; Experimental data; Quality assurance.

Nomenclature: Stace (1997).

Abbreviations: ASCII = American Standard Code for Information Interchange; AVDL = Applied Vegetation Dynamics Laboratory; BCRE = Bracken control and restoration experiments; HTML = HyperText Markup Language; PDA = Personal digital assistant.

Introduction

A great deal of experimental and observational data has accumulated throughout the vegetation science community. These data relate to phytosociology (e.g. Rodwell 1991-2000), country- and continent-wide monitoring (e.g. Corney et al. 2004; Willner et al. 2004), restoration ecology (e.g. Le Duc et al. 2000a), and experimental ecology (e.g. Bakker & Wilson 2004; Marrs & Le Duc 2000; Pakeman et al. 2003). Such data sets can be very valuable for meta-analysis (e.g. Treseder 2004) and thus may be of potential interest long after they were collected. However there are problems associated with *post priori* use, even assuming that the data are available. Major difficulties can arise from the way the data were archived. It is important that potential investigators understand all details of the way the data collection and processing proceeds, that quality assurance procedures are clear (Anon. 2005), and that the structure of the archived data is transparent (Brunt 2000). Such matters come within the scope of metadata standards, and a draft working document for the ecological sciences is available through the Federal Geographic Data Committee of the USA (Landis 2005).

The Applied Vegetation Dynamics Laboratory (AVDL) at the University of Liverpool (www.appliedvegetationdynamics.co.uk), has amassed a number of short- to long-term (up to 20 year) data sets on a number of experimental investigations and structured surveys relating to restoration ecology. The subjects were usually sites invaded by undesirable native weeds such as *Molinia caerulea* and *Pteridium aquilinum*. The AVDL work on *P. aquilinum* control has been particularly extensive and geographically widespread (Fig. 1) (Marrs & Le Duc 2000; Marrs et al. 2004; Le Duc et al. 2000b; Le Duc et al. 2003; Ghorbani et al. 2003).

Data sets assembled during these investigations have intrinsic value in supporting the published papers. They also have proven value in modelling exercises (Pottier et al. 2005), and in the current, and perhaps ever-present, perspective of environmental change (e.g. King 2005) they stand as valuable historical records. In order that the data fulfil their potential they must meet a number of requirements. The data must be stored in a fashion suitable for long-term survival; they must be readily accessible; they must be supported by clear descriptions of the context in which the study was undertaken, details relating to the formal (e.g. statistical) design of the study, and how the data were collected. A computer database system should be able to meet these requirements.

In recent years database technology has been applied to whole organism science in a number of ways. It is used to accumulate records of species presence on country-wide, and long time scales (Preston et al. 2002). The technology has also been used to store data from very large-scale, structured surveys (Bunce et al. 1996). Perhaps the most common usage has been in the field of phytosociology (Ewald 2003), and web-based databases are available for access to such records (e.g. VEGBANK, (http://vegbank.nceas.ucsb.edu/vegbank/index.jsp); Jennings et al. 2004). At least one system, TURBOVEG (Hennekens & Schaminée 2001), is generally available to store floristic data from different sampling points. However, for the purposes of AVDL, existing and available systems are not versatile enough in two areas. First, they lack facilities for handling metadata of the type generated by complex experiments and structured surveys. Second, phytosociological databases are not designed to handle data from repeated measures through time (for example, data that are intended to detect successional changes). Nevertheless they can, and have been, used for these purposes (e.g. Smits et al. 2002). In order to surmount these issues we designed a purpose-built database that would have the ability to store all AVDL data sets, with a system of standard queries for future investigations and meta-analyses. This paper describes the development of a database system, initially to hold the BCRE data, and the progress to date.

Although the system described is still at the development stage, it is intended that this contribution should focus interest on a number of issues relating to the output of scientific work in this field, and its long-term value. We consider quality assurance and control of experimental data (and metadata) collection, archiving, accessibility and dissemination, and the extensive application of meta-analysis, of great importance for the future.

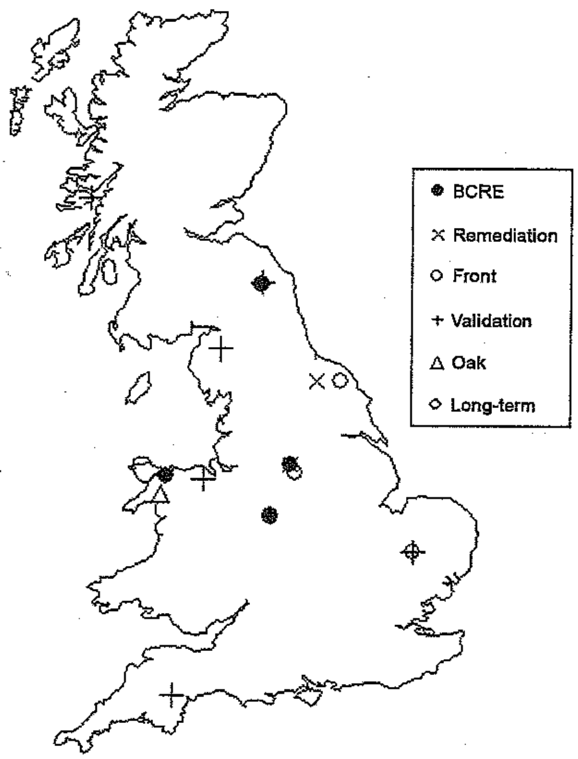

Fig. 1. Location of 18 experiments carried out to investigate bracken and its control. Some are long-term (> 10 year), some are complete. Each has generated a large amount of data. The groups of experiments are: BCRE – Bracken Control and Restoration Experiments (seven in total) located in Cheviot Hills, Snowdonia, Peak District and Cannock Chase; Remediation experiments (two, post bracken treatment), North York Moors and Peak District; Front (two, control of advancing bracken front), North York Moors and Peak District; Validation (six, validation of bracken control model), Mull, Cheviot Hills, Lake District, Clwyd Hills, Breckland, Dartmoor; Oak (one, oak regeneration and bracken control), Snowdonia; Long-term (one, bracken control and heath restoration), Breckland.

Methods

The data

The initial database project related to seven experiments set up between 1993 and 1995 at four different sites across Great Britain (Le Duc et al. 2000, 2007; Tong et al. 2006). The objective was to test established methods of bracken control, combined with vegetation restoration techniques across a wide biogeographical range (BCRE experiments, Fig. 1). Systematic monitoring data were collected twice a year from each experiment, and collection is ongoing. The monitoring data comprised measures of bracken performance, and other species' responses (including bryophytes), resulting from experimentally-applied treatments (Le Duc et al. 2000, 2007). The result was a large, and highly complex, multi-scale set of data difficult to access and requiring a systematic procedure for archiving and quality assurance. Additions were being made on a regular basis.

Database design

The AVDL has a series of requirements for the database, which came into operation in 2004. It should have a working system of metadata (Jennings et al. 2004); it should have a working system for quality control and assurance both for migrating existing data into the database and for adding new records (SAC Secretariat 2005), the data retrieval system, initially implemented via a small number of queries should produce ASCII files readily interpretable for use with standard statistical and ecological analysis programmes, e.g. CANOCO (ter Braak & Šmilauer 1998), PC-ORD (McCune & Mefford 1999), SAS (Anon. 1989), S-Plus (Anon. 1997), and R-network (Venables et al. 2002) modules such as VEGAN, GRAVY, etc. Thus, the queries were designed to produce ASCII files with complete metadata as a basic standard for archiving (Cook et al. 2001). An additional study on the possibility of extending the scope of the system was undertaken. This involved addition of a further table to define the nature of the project (survey vs. experiment), and a table to incorporate extra sample measurements.

As a preliminary to the database design, an entity relationship diagram (Chen 1976) was produced (Fig. 2). The database was developed using Microsoft software, including SQL Server 2000 (Otey & Conte 2001) running in Windows 2003, the Internet Information Service package IIS 5.0, and the web applications builder ASP. It had a common data structure, storing the data in a formal format (Vincent & Srinivasan 1993), and is capable of exporting data in a range of formats.

A three-stage system for database backup was also established. First the SQL server backs up the database automatically (based on 'Backup Plans', Otey & Conte 2001). Second, backup files are transferred manually to other storage media, such as CDs or stand-alone hard drives, on a regular basis, and a CD-based copy is held off-site at all times. Finally, a web site backup is executed manually by the DB Administrator, and a mirror site runs in parallel thus ensuring integrity of the primary database and protection against a web site crash.

Quality assurance

Quality assurance (QA, establishing good practice, including appropriate QC procedures) and quality control (QC, testing and auditing the procedures and output from the system) are key factors in handling complex data sets. They are crucial in the processes of designing experimental or survey investigations, collecting and coding data, and in auditing electronic files (Edwards 2000). Thus QA/QC was involved at all of these stages in assembling the BCRE database.

Once electronic data files were created, a system of filtering (by setting appropriate database field limits) for illegal data was set up (Table 1). The filtering was applied to both data and metadata and necessitated tables of possible values and ranges (Edwards 2000). Illegal data checks could be carried out after entry to the database was completed. In this way quality audit reports were generated.

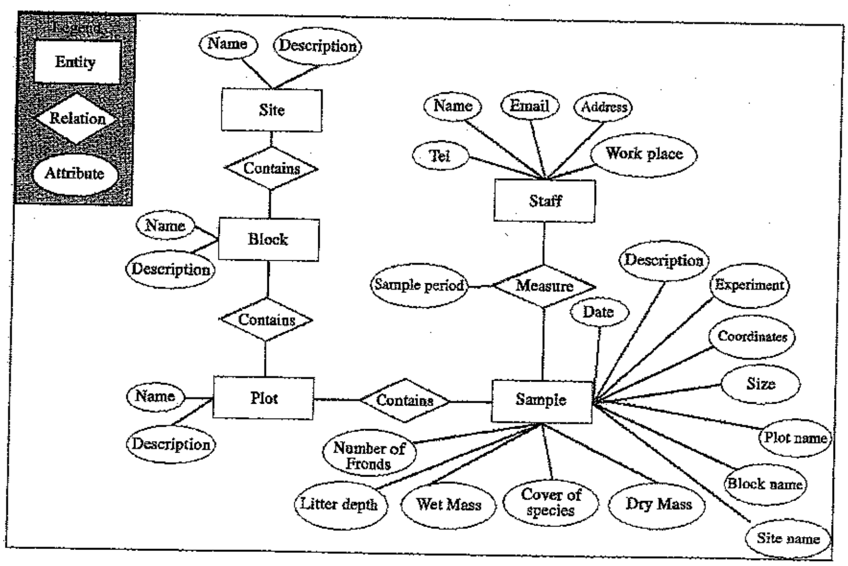

Fig. 2. Entity Relationship Diagram for the AVDL database.

Table 1. Examples of the quality control system: **(a)** validation rules to check integrity of the data during transfer into the AVDL database; **(b)** permissible number of quadrats; **(c)** permissible plot co-ordinates.

(a)

Rule number	Definition
1	**Sampling date(s),** the calendar-date(s) on which the data were logged at the experiment. The logging may take place over a number of dates.
2	**Experiment codes** (*EC*) to be within limits per experiment (see Table 1b), with all combinations entered.
3	**Number of plots,** N_i, is the 'number of combinations' given in Table 2.
4	**Plot codes** (*PC*) to be within limits per experiment and running consecutively (1 to N_i), but not necessarily in same alphanumeric order as ***EC*,** and probably having a different sequence in relation to ***EC*** every year.
5	**Number of quadrats per plot** (n_q) to be correct per experiment per sampling season (see Table 3b).
6	**Total number of quadrats sampled** (N_q) to be correct per experiment per sampling season, and $N_q = n_q.N_i$.
7	**Quadrat coordinates** (*QC*) to be within limits per experiment (see Table 3c), with n_q per ***EC***. The coordinates should be unique per experiment across all sampling dates.
8	**Species codes** (S_j) to be within limits set by the **Species dictionary** table.
9	**Number of species** (n_j) per quadrat per sampling date to be $0 \leq n_j < 35$.
10	**Total number of species** (N_j) per experiment per sampling date to be $5 \leq N_j < 75$.
11	**Cover (%)** per individual **species** present (see rule 8) per quadrat given by $0 < w_{ij} \leq 100$.
12	**Other cover codes** (O_k) within limits set by the **Species Dictionary** table. There may be no **other cover** in a particular quadrat, thus the field may be empty.
13	**Cover** (%) per individual **other-cover** item present (see rule 12) per quadrat given by $0 \leq w_{ik} < 100$.
14	Total of **Cover** (%) **per quadrat** ($W_i = w_{ij} + w_{ik}$) given from by $85 \leq W_i < 300$. Also with *Pteridium aquilinum* (pteraqui, species code 24) excluded the following limits $80 \leq (W_i - w_{i(pteraqui)}) < 230$ also apply. Any sample data collected after 2004 including 2004 obey $90 \leq W_i < 300$ with *Pteridium aquilinum* (pteraqui, species code 24) and $90 \leq (W_i - w_{i(pteraqui)}) < 200$ without *Pteraqui* rules.
15	**Litter depth** per quadrat (Ld_q cm) to be within limits given by $0 \leq Ld_q < 75$.
16	**Number of fronds** per quadrat (Fc_q) to be within limits given by $0 \leq Fc_q < 65$.
17	**Frond length** (*Fl* cm) to be within limits given by $0 < Fl < 300$. If no fronds are present in a quadrat then no record is made, zeros are not allowed. Hence the field may be empty.
18	Number of entries for **Frond length** per quadrat (n_{Fl}) is then subject to the requirement $n_{Fl} = Fc_q$.
19	**Frond dry mass** (Fm_q g) per quadrat to be within limits given by $0 \leq Fm_q < 1000$.

(b)

Sample quadrats per sub-(sub-)plot in:

Experiment	June	August
Sourhope2	3	2
NorthPeak	2	1
Carneddau	2	1
Cannock1	3	2
Cannock2	3	2
Cannock3	2	1

(c)

Experiment	Sub-(sub-)plot (*X,Y*) coordinates in: 1993	1994	1995	1996	1997	1998 to 2003
Sourhpe1	0 to 9,0 to 39	0 to 9,0 to 17	as 1994	as 1994	as 1994	as 1994
Sourhpe2	-	0 to 9,0 to 39	0 to 9,0 to 17	as 1995	as 1995	as 1995
NthPeak1	0 to 9,0 to 39	0 to 9,0 to 4	as 1994	as 1994	as 1994	as 1994
Carnedd1	0 to 9,0 to 39	0 to 9,0 to 39	0 to 9,0 to 11	as 1995	as 1995	0 to 9,0 to 4
Cannock1	0 to 9,0 to 39	0 to 9.0 to 11	as 1994	as 1994	as 1994	as 1994
Cannock2	0 to 9,0 to 39	0 to 9.0 to 11	as 1994	as 1994	as 1994	as 1994
Cannock3	-	-	0 to 6,0 to 9	as 1995	0 to 6,0 to 4	as 1997

Data output

Two methods for extracting data were available. First, it was possible to obtain HTML format tables of the data by specifying the metadata. Second, a number of standard Queries, based on predictions of the most likely requirements of a user, were programmed. These were controlled by metadata, such as date and experiment identity, and related to variables for: species presence and cover; cover of non-living items; *Pteridium aquilinum* production measures. Each Query was accompanied by an extensive notes page specifying metadata for the requested data tables. Output was either in HTML or ASCII format. The Query list can be added to when necessary.

Results

The database comprised four sub-classes of tables: the system log and user-control tables; experiment tables; sample data tables; QA/QC rules tables (Table 2).
By the end of 2004 the database contained 13 770 sample (quadrat) data entries for the period 1993 to 2004. There were 86 387 entries on 218 species, and 83 379 on bracken frond specimens.

After data entry up to and including the 2004 season was completed, and rules for filtering out illegal data (and metadata) were established (Table 1), a full quality audit was run. This uncovered a total of 4690 (2.06% of total entries) illegal data. The nature and consequences of these illegal entries were diverse, and a broad breakdown of types is shown (Fig. 3). In most cases it was possible to trace the causes of the problems.

Thus the filtering process had major advantages. After identification of illegal data entries arising from DB design, programming and file handling, these could be corrected. Also those errors identified as arising from the coding process could be corrected by reference to the original field sheets. This also gave an estimate of the error level, due to coding, that was not detected by filtering. However illegal entries detected as arising from mistakes made in the field were mostly impossible to correct, and in such cases the entries were changed to show 'missing data'. Nevertheless, this process allowed insight into the extent and type of errors originating in the field, and the possibility of improving future data capture.

In a few cases it was determined that the initial quality control criteria were unrealistic, i.e. too stringent, and these were also updated. For example, the 'Total of cover (%) per quadrat' (item 14, Table 1a) had to be increased after re-examination of field sheets for complex multi-layered vegetation. After this procedure of re-examining the filtering limits, by reference to those field sheets flagged by the process, was complete the database was considered to be ready to go on line. At this point <0.5% of records had been found to be illegal due to recording errors; these were replaced by 'missing data'.

The database was then made available on a limited basis at the web site: <www.appliedvegetationdynamics.co.uk>. A password-protected entry system enabled new record entry (with quality checks) by local staff, and data output via the internet. An example of an ASCII output file is shown (Table 3). Whilst it is not the intention for others to have data entry rights at the time of writing, it is certainly possible in principle. Workers wishing to access the existing data should contact the AVDL.

At this stage it was possible to produce multi-experiment and multi-site sets of data in ASCII format and with the appropriate metadata. As an illustration a single species analysis was carried out using repeat-

Table 2. The four sub-classes of database tables. All database tables except 1 and 3.4 are metadata.

Sub-classes/ Description	Comments
1. System log and User tables	
1.1. The system log	
1.2. User's login information	
1.3. User access privilege	
2. Experiment tables	
2.1. Experimental design details	
2.2. Descriptions of experimental areas	
2.3. Species dictionary	Can be linked with trait data
3. Sample data tables	
3.1. Monitoring design data	
3.2. Geographical data	
3.3. Sample metadata	Coordinates, recorders, sample size
3.4. Detailed data	Species cover, plant metrics
4. QC/QA rules tables	
4.1. Rules and parameters for error checking	

measures ANOVA with the SAS statistical programme using polynomial contrasts (Anon. 1989). This related to the performance of *Agrostis vinealis* at the two Cheviot experiments over the experimental period 1994-2003 (Fig. 4). The figure revealed a complex result comprising two levels of response. At the general level of response an overall increase in abundance was seen at one site, and a simultaneous reduction at the other. At a shorter timescale the species was responding in a cyclic (2-year period) fashion, with the sites in phase.

Finally a feasibility study was successfully completed on incorporating into the database a large set of survey data. The survey (Le Duc 2000a) was of sites throughout the UK that had undergone treatment for bracken control. To achieve this it was essential to add tables for project definition and design to the DB structure (Fig. 2). The versatility of the ensuing structure was found to be adequate for this feasibility study in the sense that information retrieval could be achieved satisfactorily. Other datasets may require similar modifications to the structure.

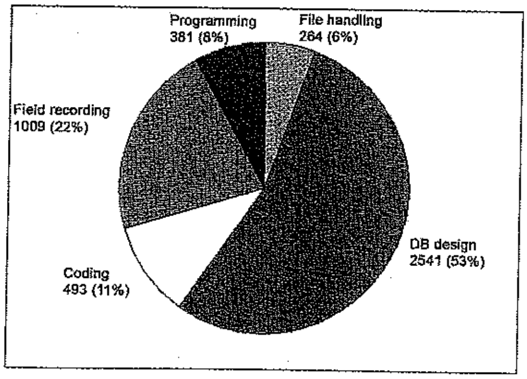

Fig. 3. The numbers of illegal entries detected in all (BCRE 1993-2004) imported data, broken down by categories (figures in brackets are % of all illegal entries). The sum of all illegal entries represents 2.06% of total entries in database.

```
Query: ALL SPECIES COVER
*********************************************
Project Name: BCRE
Sample Year: 1996
Site(s): NthPeak1
Main Treatment: Cut twic per year (Cut2pa)
Sub Treatment: Fenced exclosure (Fenced)
Sub Sub Treatment: Calluna brash & nurse (CvBr_Acs)
Each quadrat (row) has a unique code (SampleID)
Quadrat Size: 1m x 1m
Species:
(7) Calluna vulgaris (Callvulg)
(9) Vaccinium myrtillus (Vaccmyrt)
(10) Galium saxatile (Galisaxa)
(14) Festuca ovina (Festovin)
(17) Deschampsia flexuosa (Descflex)
(22) Agrostis capillaris (Agrocapi)
(24) Pteridium aquilinum (Pteraqui)
(26) Campylopus pyriformis (Camppyri)
(29) Dicranum scoparium (Dicrscop)
(36) Hypnum jutlandicum (Hypnjutl)
(48) Carex pilulifera (Carepilu)
(54) Chamerion angustifolium (Epilangu)
(98) Agrostis castellana (Agrocast)
Units: Cover %
Notes: '-' = Measurement not made
*********************************************

SampleID Date Site Block Main_Trt SubTreat SubSubTr Callvulg Vaccmyrt Galisaxa
Festovin Descflex Agrocapi Pteraqui Camppyri Dicrscop Hypnjutl Carepilu Epilangu
Agrocast
---------------------------------------------
56709 19/06/1996 NthPeak1 A Cut2pa Fenced CvBr_Acs 0 0 0 0 50 0 30 0 0.1 1 2 0 0
56710 19/06/1996 NthPeak1 A Cut2pa Fenced CvBr_Acs 0 0 0 0 3 0 10 0 0 0 0 0.1 0.1
56773 19/06/1996 NthPeak1 B Cut2pa Fenced CvBr_Acs 0 0 30 2 25 0 3 0 0 0 0 0 0
56774 19/06/1996 NthPeak1 B Cut2pa Fenced CvBr_Acs 0 0 0.1 10 70 0 3 0 0 0 0 0 0
56841 21/06/1996 NthPeak1 C Cut2pa Fenced CvBr_Acs 2 0 0 0.1 5 1 10 1 0 0.1 0 0 3
56842 21/06/1996 NthPeak1 C Cut2pa Fenced CvBr_Acs 0 3 50 5 20 0 2 0.1 0 0 0 0 2
|
```

Table 3. ASCII file output from a standard query.

Discussion and Conclusion

A purpose-built database has been developed for handling multi-site experimental data, and is now in use. The QA/QC aspect of this system is a major advantage, allowing much effort to be saved in data collection and entry. The system has brought several other major advantages, including access across the internet, simplified data back-up, and efficient archiving.

With careful use of metadata it is now possible to obtain complex data sets, in ASCII format, thus simplifying the process of data preparation for analysis. More complex outputs, such as those required for specific analytic programmes, are as yet not available; further database programming would be required. However the standard format ASCII output is relatively simple to manipulate. With broader-based analyses greater insights into species response are possible.

Access via the internet makes it possible to use the system remotely. In this way it could upload data directly from the field using PDA technology. The database might also be developed as an experimental design tool, whereby good statistical practice could be defined using the QA/QC checking system (Fig 5).

Extending the scope of the database was shown to be possible. One other dataset, the result of a survey, was

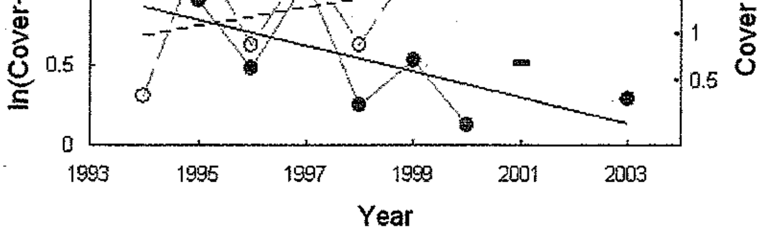

Fig. 4. The *Agrostis vinealis* result from Sourhope (open circles = Expt 1, closed circles = Expt 2). Analysis was using the repeated measures function in SAS (Anon. 1989) along with polynomial contrasts and Bonferroni-corrected error rates. The result was a first order effect (shown by the least-squares fitted lines) with $F_{(1,2)} = 13700$*. Error bar is standard error of the difference of means.

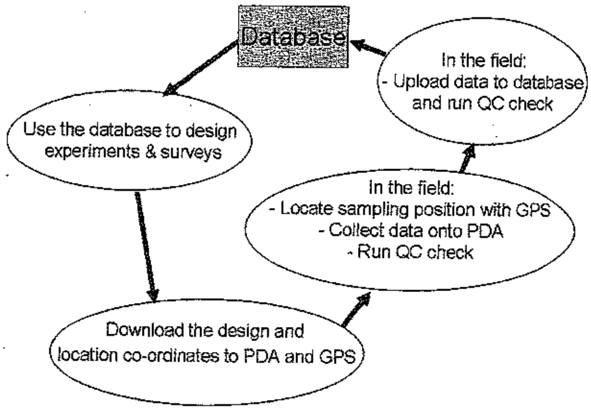

Fig. 5. The future direction.

successfully mounted. Programming for appropriate query outputs has yet to be done. Thus it is possible to generalise the system to include data from a number of different projects (e.g. Fig. 1). In this way a major meta-analysis study for the AVDL bracken control experiments would be possible.

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