Journal of Environmental Management (1993) **39**, 121–142

A Computer System for Catchment Management: Background, Concepts and Development

D. C. Le Maitre, B. W. van Wilgen and D. M. Richardson

Division of Forest Science and Technology CSIR, Jonkershoek Forestry Research Centre, Private Bag X5011, Stellenbosch 7600, South Africa

Received 10 *August* 1992

Managers of natural areas require a wide variety of up-to-date and accurate information and maps to manage their lands effectively. This paper reviews the objectives of conservation management, and the problems faced by mountain catchment managers, in the Cape Province, South Africa. The manager's information requirements, system design concepts and the first phase of the development of a computerized database are described. The system has two components: a spatial database developed using geographic information system (GIS) software on a workstation, and a desktop computer database (PC system) developed using a standard relational database package. The GIS is used to generate the links that the PC system uses to associate spatial entities such as land ownership boundaries, land management units (compartments) and vegetation types. It also used to calculate spatial statistics such as the area of a compartment or vegetation type or the length of a road or path. A variety of maps are produced, including an opaque base map and clear overlay maps showing features such as compartment and fire boundaries, post-fire vegetation age and the distribution and density of alien weeds. It also has routines to calculate fire hazard based on post-fire age and fuel accumulation models for the different vegetation types occurring in the catchment areas. The PC system gives the manager access to his data and provides a scheduling routine for assigning priorities for planned fires. Future developments will include an expert system for planning control operations for alien plant species.

Keywords: land management, conservation, information systems, GIS, fire management.

1. Introduction

The advent of inexpensive and powerful desktop computers has made geographic information systems (GIS) available to a variety of users. There is tremendous potential for using GIS to advance the management of natural and transformed land areas (Kessell, 1990). Applications have been developed for land and vegetation classification (Davis and Dozier, 1990; Moore *et al.*, 1991), fire behaviour prediction (Kessell, 1990; Zack and Minnich, 1991), animal movements and activities (Folse *et al.*, 1990) and land and forest planning (Brinkman, 1990).

0301–4797/93/100121 + 22 $08.00/0

Until recently, land managers have had to depend largely on written records and hand-drawn maps and map overlays for the information they require when making decisions. Modern geographic information systems combine both spatial and non-spatial data with analytical facilities which can meet the key information requirements of managers and ensure that they have access to up-to-date information (Kessell, 1990; Brinkman, 1990).

In South Africa, the idea of developing a computer database for catchment management arose a number of years ago from informal discussions between field managers and researchers. Initially, the idea was develop a database system without any GIS component. Over time, and with the realization that modern computers and software made it possible and practical to combine spatial and non-spatial data, the idea of integrating maps and management information in a single database was conceived.

In this paper we describe the concept and development of a geographic information system and database designed to meet the needs of managers of extensive areas of natural vegetation in the mountain catchments of the Cape Province of South Africa. We begin with a brief description of the complexities of the environment and vegetation. Then we describe the current situation and problems, the aims, design and development of the system and, finally, the developments that may follow.

2. Environment

Most of the remaining natural vegetation in the south-western, southern and eastern Cape Province is in the mountain areas (Rebelo, 1992). The mountains are important catchments, providing the water supplies for the lowland agriculture, towns and cities (Van der Zel and Walker, 1988). Fortunately, the requirement for sustained supplies of high-quality water is compatible with the goals of conservation management (Van Wilgen *et al.*, 1992).

2.1. CLIMATE

The climates of mountain catchment areas of the Cape Province are heterogeneous. In the south-west, the climate is mediterranean, with 60% or more of the rainfall in the winter (Specht and Moll, 1983; Deacon *et al.*, 1992). In the south and east, there is a bimodal pattern as summer rainfall becomes more important towards the east. Strong, warm south-easterly winds are an important factor in the southern regions and warm, dry (berg) winds from the interior plateau are more frequent in the south and east (Specht and Moll, 1983; Deacon *et al.*, 1992) and are associated with a high risk of fires (Van Wilgen, 1984).

2.2. SOILS

The soils of the montane areas are derived primarily from the hard, quartzitic sandstones of the Cape Supergroup and are shallow, poorly developed and have a very low nutrient status (Kruger, 1979; Campbell, 1983). There is a gradient from west to east and the finer sandstones in the south and east result in finer, better-developed soils with a higher nutrient status. The shales of the Karoo Sequence are more important on the lower slopes and foothills and give rise to deeper loamy soils with a relatively high nutrient status (Kruger, 1979; Campbell, 1983; Deacon *et al.*, 1992).

2.3. VEGETATION

On soils derived from sandstone, the dominant vegetation is fynbos, a species-rich, fire-prone shrubland. In moist areas on the lower to middle slopes, fynbos has a three-layered structure with an understorey dominated by low shrubs, reeds and sedges, the mid-storey by tall reeds and shrubs and the overstorey by tall shrubs (Kruger, 1979; Campbell, 1985; Cowling and Holmes, 1992). In drier areas, and on the upper slopes, the overstorey is sparse or absent, except on sheltered slopes where a tall closed shrubland develops. On coastal slopes under low rainfall, or on shale-derived soils, the fynbos grades into renoster shrublands, currently dominated by small-leafed shrubs and annuals but probably originally by grasses (Cowling, 1984). On inland mountain ranges, the fynbos grades into renoster shrublands, succulent thicket and karoo shrublands dominated by perennial shrubs, succulents and annuals. On the coastal slopes of the Outeniqua and Tsitsikamma mountains, temperate forests form a mosaic with the fynbos. In the east, there is a complex mosaic of karoo shrublands, sub-tropical thicket, succulent thicket and grassy fynbos, with divergent management requirements (Cowling, 1984; Cowling and Holmes, 1992).

2.4. FIRE REGIMES

There is a natural gradient in fire frequency from west to east which is linked to the increasing importance of grasses and lightning (Edwards, 1984). The probability of a fire increases with time, reaching a value of about 0·5 at a post-fire age of 12–15 years, compared with grasslands at 2–3 years of age (Van Wilgen *et al.*, 1991; Le Maitre and Midgley, 1992). This is also linked to a gradient in fire season. The peak fire season in the west is in the late summer and autumn. In the southern coastal areas, fires are more dependent on the occurrence of bergwinds, which are most common in winter, and the peak fire season is in the winter in the eastern grasslands (van Wilgen, 1984; van Wilgen *et al.*, 1991; Le Maitre and Midgley, 1992).

Fire is the primary regenerative factor in fynbos. Many species, notably the tall fire-killed shrubs of the Proteaceae, are sensitive to changes in fire season and fire frequency. Fires that occur before the proteas have matured or after they senesce can result in local extinction (Bond, 1980; Van Wilgen, 1981; Van Wilgen *et al.*, 1991; Le Maitre, 1992). Regeneration is also poor after fires in winter and spring, compared with fires in summer or autumn, and repeated winter or spring fires could result in species extinction (Bond, 1984, 1990). This means that management options are strongly constrained by the requirements of these species and can vary between catchments depending on plant traits (Van Wilgen *et al.*, 1992).

Fires are rare in karoo, thicket and forest (Van Wilgen *et al.*, 1990), primarily because there is too little fuel or it is too sparse. Virtually nothing is known of the occurrence of fires in transitional vegetation types. Management requirements of forest vegetation are relatively well understood because they have been studied intensively (Seydack *et al.*, 1990), but little is known of the other vegetation types. Fires in renoster shrublands were probably at least as frequent as those in fynbos but, again, there are no records to base this conjecture on. The primary driving factor in karoo shrublands and succulent thicket is rainfall, which appears to regulate reproduction and recruitment, along with grazing and browsing by herbivores, but the dynamics of these vegetation types are poorly known (e.g. Hoffmann *et al.*, 1990; Yeaton and Esler, 1990). Thus, while there is a reasonable understanding of the fire ecology of fynbos, there are few guidelines for managers who have to manage other vegetation types.

TABLE 1. Management objectives in Cape conservation areas (Anon., 1990)

Ecosystem conservation	the management, conservation and protection of integrated ecosystems (represented by the natural vegetation and fauna of an area), to ensure the maintenance of maximum genetic diversity of plant and animal communities, and to maintain systems in a stable condition
Catchment conservation	the management and conservation of catchment areas to ensure the sustained yield of high-quality water and to keep erosion to a minimum
Species conservation	the management and conservation of rare and threatened species of plants and animals, especially those that are endemic to particular areas
Utilization	to provide opportunities for wise utilization of resources, including facilities for outdoor recreation
Education	providing education programmes and centres and extension services to engender a conservation ethic in the total population
Cultural conservation	compilation of inventories and maps, protection and interpretation for the public

3. Management

3.1. MANAGEMENT STRUCTURE

The management of the state conservation areas in the Cape Province, excluding the National Parks, is the responsibility of the Chief Directorate of Nature and Environmental Conservation (CDNEC) of the Cape Provincial Administration. They manage 90 nature reserves, state forests and wilderness areas, with a total area of approximately 1·24 million ha, about 4% of the Cape Province (Anon., 1990). They are also responsible for managing 614 000 ha of private land proclaimed under the Mountain Catchment Areas Act, under which they can prescribe management actions and enter into contracts to manage these areas for the land owners. The Cape Province has been divided into four adjoining regions for conservation management: Western, Southern, Eastern and Northern. Catchment management is not important in the Northern Cape, so this area is not discussed further in this paper. Each of the remaining regions (except the Southern) is divided into districts which each comprise two or more catchment management centres. Management centres usually comprise complete mountain ranges or natural mountain units. The state land and proclaimed catchment area together vary from 40 000 to 120 000 ha per centre.

3.2. MANAGEMENT GOALS AND OBJECTIVES

The policy of the CDNEC is to maintain essential ecosystem process, conserve genetic diversity, ensure sustainable utilization of natural resources and preserve the cultural heritage (Anon., 1990). These goals are derived from those set by the IUCN in its World Conservation Strategy and provide the basis for more detailed management objectives for conservation areas (Table 1).

3.3. MANAGEMENT POLICIES AND PHILOSOPHIES

Management policies differ between regions and districts because of differences in the environments and fauna and flora, population densities and management philosophies (Richardson and Le Maitre, 1991). The Western region has the longest management history, the greatest density of people and the most highly developed and intensive agriculture (Deacon, 1992). The mountain ranges are narrow so management units are small and management is relatively intensive. The primary management tasks are to carry out planned burns and control invasive alien plants (Wilson, 1985). The southern and eastern regions have extensive areas with little or no human activity and extensive dry-land agriculture and grazing (Deacon, 1992). Large areas are managed under a *natural burning regime* which allows fires started by natural agents, primarily lighting, to burn unhindered, except where there is a strong risk that the fire will spread to adjacent private lands. The primary management task is alien plant control (Seydack, 1986). Additional tasks, such as recreation management and erosion control, vary in importance within and between regions (Richardson and Le Maitre, 1991).

4. General problems facing catchment managers

4.1. FIRE MANAGEMENT

Fynbos shrublands are renowned for their rich flora, and the conservation of biotic diversity has a high priority (Anon., 1990; Cowling *et al.*, 1992; Van Wilgen *et al.*, 1992). Research has shown that mismanagement of the fire regime can result in species extinction. Although fynbos can burn 3–4 years after a fire, most of the tall shrub species only accumulate sufficient seeds to ensure replacement after 8–12 years (Van Wilgen *et al.*, 1992; Le Maitre, 1992). There is, therefore, a long period during which fires are possible but not desirable. Fire intensities also increase with age depending on the quantity and distribution of fuels. Under dry summer conditions fire intensities can be high even in relatively young fynbos and fires in old stands can be difficult to control and dangerous (Van Wilgen *et al.*, 1991).

Current knowledge of plant population dynamics in fynbos catchments is restricted almost entirely to the tall shrubs of the Proteaceae. Reliable quantitative data on important aspects, such as seed bank dynamics, are lacking for most species (Van Wilgen *et al.*, 1992). The rich flora and the lack of simple identification keys makes monitoring of species diversity for the detection of changes and trends impractical. Therefore, the approach has been to identify key species which are killed by fires, slow to mature, widespread and easy to identify in all life stages (Richardson *et al.*, in prep). The best candidates are the Proteaceae; sufficient data are now available on their population dynamics and responses to different fire regimes to define optimal fire regimes (Van Wilgen *et al.*, 1992). However, the optimal regime for the proteas may not be equally beneficial for all species and a fire regime that results in dense, closed, tall shrublands may bring about species losses (Cowling and Gxaba, 1990).

4.2. MANAGEMENT OF ALIEN WEEDS

Fynbos appears to be exceptionally vulnerable to invasion by tall, woody, fire-adapted plants (Richardson *et al.*, 1992). Alien plants disrupt many ecosystem processes and are a major problem for managers. The major alien species can be divided into two groups with differing reproductive ecology and control requirements. The first group, comprising species with wind-dispersed, canopy-stored seeds, includes pines (*Pinus pinaster*, *P. radiata*, *P. halepensis*) and Australian *Hakea* species (*Hakea sericea*, *Hakea gibbosa*). These species are generally killed by fire and are controlled by felling them to induce seed release and germination, and then burning to kill seedlings. The second group, comprising the Australian *Acacia* species (*A. cyclops*, *A. saligna*, *A. longifolia*, *A.*

pycnantha and *A. mearnsii*), has persistent seed banks in the soil. *Acacia saligna* and *A. longifolia* are also able to sprout after fires or being felled. These species are more difficult to control because they have large seed banks and recruit huge numbers of seedlings. This, combined with relatively rapid maturation, makes frequent and long-term follow-up actions essential. Biocontrol agents have been introduced for *Hakea sericea* and *Acacia longifolia* and have been successful (Van Wilgen *et al.*, 1992).

Pine plantations can reduce the streamflow from fynbos catchments by up to 80% and can turn perennial streams into seasonal ones (Van Wyk, 1987). The influence of other alien species is not known, but it is reasonable to assume that they would have similar effects. The potential reduction in water supplies has been a major factor motivating alien plant control operations, despite the budgetary constraints (Richardson *et al.*, 1992). Up to 75% of the total budget for conservation in some areas is spent controlling alien plants, so effective methods of control are important. Effective control measures for single species are available, but the problem becomes very complex in mixed-species stands. No decision models or prescriptions exist for these situations, and managers base their decisions on personal experience.

4.3. WATER SUPPLIES

South Africa is largely arid and drought-prone, so water supplies have always been a problem (Wicht, 1945; Van der Zel and Walker, 1988). The marked altitudinal gradients in rainfall and concentration of arable soils in the foothills and lowlands result in intensive agriculture being generally heavily dependent on water from the catchments (Van der Zel and Walker, 1988). Frequent burning can increase streamflow in some catchments (Bosch *et al.*, 1986). However, fire cycles of 12–15 years are considered most appropriate for meeting water needs without degrading the catchments (Richardson *et al.*, 1992). Thus, management actions are aimed at ensuring that water quality is maintained and erosion control has a high priority (Wilson, 1985; Seydack, 1986; Van Wilgen *et al.*, 1992). However, there are divergent opinions among farmers on the effects of fire on water supplies and managers are often under considerable pressure to increase water supplies by burning more frequently.

4.4. WILDFLOWER HARVESTING

There is a large industry, with an annual turnover of about R32 million, involved in the harvesting and export fresh and dried wildflowers and other plant products (Anon., 1990). Wildflower cultivation and harvesting has been restricted largely to private mountain lands. There is, however, increasing pressure from the industry to harvest on state lands, and managers are considering this as an option for raising the funds they need to manage the catchments effectively (Richardson and Le Maitre, 1991). Wildflower harvesting is regulated by permits from the CDNEC (Anon., 1990) but it is difficult to police picking operations. It is also difficult to obtain information on who is harvesting what species (and what parts of those species) and where they are harvesting them, as this information cannot readily be collated.

4.5. POPULATION GROWTH

South Africa has a rapidly increasing urban population. There is already considerable pressure on existing recreation facilities in mountain areas, especially for intensive uses such as camp and picnic sites. As the living standards or urban populations rise this pressure will increase. Thus, there is considerable pressure on the authorities to provide and maintain more facilities (Anon., 1990). It is difficult to obtain the environmental information that is needed to plan recreation facilities, and some means of collating and organizing the available information is urgently required (P. Hill, pers. comm., 1991).

The rapidly increasing population also leads to an increasing demand for potable water, but the supplies are finite and the development of systems for ensuring that the water is divided fairly between the consumers has a high priority (Van der Zel and Walker, 1988).

4.6. PUBLIC OPINION AND LIMITED FUNDS

Finally, managers are under pressure to demonstrate that their management systems are effective and that they are achieving their goals. They must also be able to show that what they are doing is ultimately beneficial to all the citizens of the country. Catchment management is expensive and budgets are shrinking. The only route to follow, without lowering standards, is to ensure that funds are spent as effectively as possible. This cannot be achieved without access to reliable and up-to-date information.

5. Management information needs

The information requirements of land managers were determined by conducting a survey of catchment managers, senior managers, researchers and planners from the Western, Southern and Eastern Cape Regions of the Chief Directorate of Nature and Environmental Conservation. Managers and appropriate people in other governmental and statutory bodies were also interviewed. In each interview with field managers they were asked to:

1. define their management objectives (see Table 1);
2. then to identify the tasks they carried out to achieve these objectives;
3. then to identify the decisions that were made in planning and executing these tasks; and
4. to identify the information they used in making their decisions and the sources of this data (Richardson and Le Maitre, 1991).

The survey found that field managers had the same basic requirements in all the regions of the Cape Province, although the same information was often used differently in different regions. The emphasis on natural burning zones in parts of the Southern and Eastern Cape regions meant that managers did not consider planned burns except for special purposes such as providing grazing for the rare mountain zebra (*Equus zebra zebra*).

5.1. DATA ORGANIZATION AND FLEXIBILITY

The primary requirement is for an effective system for organizing and integrating the information which is currently available, but widely scattered and essentially unusable, and maintaining it in a usable form. This information includes records of past management actions on files, mapped information, records of field observations,

TABLE 2. Key weaknesses in the current practice of keeping data on management land units (compartments) in ledgers and files

It is difficult to organize the ledger so that it contains all the data required for frequent decisions in a single place
Although historical records can be kept, detailed records have to be kept in separate documents and files
Cross-referencing, extraction and collation of data must be done manually
Much of the information is more easily presented and interpreted in map form but the information has to be transferred and coded manually

information from publications and informally documented or undocumented experience (Richardson and Le Maitre, 1991).

The next major problem lay in planning annual and longer-term operations. Many management actions are dependent on preceding actions and timing may be important. For example, successful control of certain alien species may depend on the removal of saplings before they produce seeds (Van Wilgen *et al.*, 1992); managed fires are restricted to certain times of the year by ecological and safety considerations (Van Wilgen and Viviers, 1985) and must be preceded by weed clearing (if weeds are present) and the preparation of tracer lines. Drawing up these plans is time-consuming and a single wildfire can negate all planning. Funds are always a problem and an objective procedure is required for scheduling priorities.

5.2. THE CURRENT PRACTICE

The current system depends largely on maintaining one or more ledgers with records for each management unit (compartment), called the compartment register. This system has several key weaknesses (Table 2) and is no longer used by some managers (Richardson and Le Maitre, 1991).

5.3. PRODUCTION OF REPORTS

Reports consisting of maps and a description of the fire, including its origin and cause, are compiled for each wild fire $\geqslant 10$ ha and all planned fires. These reports are kept in files but there is no simple way to cross-reference data from different fires. Although information on recreation demand, such as the type of user, can be obtained from copies of permits, there is no system for collating this data effectively for analyses of trends or seasonal patterns. Nor is there a way of relating this information to the impacts of the users on these facilities.

5.4. KEEPING DATA CURRENT AND COMPLETE

It is very difficult to obtain up-to-date maps of information such as the distribution and densities of alien plant populations. Fires are now generally well documented and mapped but it is difficult to obtain information on past fires in the same area, often because the older maps have been discarded. Fire hazard information is coarse because it is usually mapped using current vegetation age only and does not differentiate between vegetation types with different fuel dynamics. Updating of maps is time-consuming. The

TABLE 3. Aims and guidelines set for designing and developing the Catchment Management System

It must: collate and integrate the information which is currently available on paper, maps and in computer information systems and present it in a usable form;
provide direct and uncomplicated access to basic data, facilities to edit and update the data, and the ability to construct queries and produce summaries;
provide mapped information on vegetation, fire history and current fire hazard, land ownership, land use, infrastructure, etc.;
provide summaries of information that can be used by the manager to monitor the effectiveness of his planned and natural burning practices and alien plant control operations;
simplify planning of annual and longer-term operations by providing a model for scheduling managed fires according to set priorities;
provide a rule model or expert system for planning and setting priorities for controlling invasive alien plants;
be designed to accommodate senior manager's information requirements by being able to summarize data for management districts and regions

effectiveness of maps is often increased by producing them on transparent media which allow the manager to overlay them to obtain additional information. These overlays have to be produced by hand.

5.5. QUANTIFYING SPATIAL INFORMATION

It is time-consuming to obtain quantitative spatial data for use in reports or budgets. For example, fire reports require the area burnt in a fire to be sub-divided according to land-ownership categories and vegetation types. It is difficult to determine the unit costs of management operations, e.g. man-days per unit area, because the area that was treated is not known. This makes it difficult for managers to budget for similar operations in the future.

5.6. ACCESS TO, AND USAGE OF, SCIENTIFIC AND SPATIAL DATA

Much of the research on the ecology of the different vegetation formations has been published in scientific journals which are not available to, or readily understood by, managers. This means that important ecological insights and solutions to management problems may not be implemented. The development of rule models incorporating these solutions will help to ensure that research results are realized.

There is an urgent need for up-to-date guides to, and maps of, paths and trails, accommodation facilities and natural features for use by the public. A GIS can be used to maintain this data and produce revised maps showing changes and additions to routes and facilities at a lower cost than manually producing updated maps and printing them.

5.7. AIMS OF THE COMPUTER SYSTEM

The best way to meet the user's requirements is to develop a database system to hold both spatial and non-spatial data. On the basis of the requirements identified during the user survey, aims and guidelines for designing and developing the system were defined (Table 3). The users considered the ability to access, update and modify their own data to be a fundamental requirement (Richardson and Le Maitre, 1991), so this was given high priority. Allowing users to modify data in a database system is risky but the managers are willing to accept ultimate responsibility for their own records. Past experience has shown that centralized data analysis systems are not always effective and reliable and the ability to obtain answers and statistics simply and rapidly will be an important incentive to use the system. Similar problems have been experienced elsewhere (e.g. Kessell, 1990), supporting the philosophy of maximizing the direct involvement of managers in the running of the system.

6. System design and development

Well-designed computer databases provide systematic data storage with minimal duplication, ready access to data and the ability to construct queries and summaries of information in reports (Kessell, 1990). The flexibility of modern GIS software, with its increasingly sophisticated analytical facilities, meets most requirements for analysis and presentation of spatial data (Brinkman, 1990). Database systems allow for the construction of simple rule models using logical operators which are adequate for a scheduling system for planning fires. More sophisticated decision models will require more complex rule models or expert systems.

The approach taken with this system differs from that of the Geographical Information and Modelling System (GIMS) described by Kessell (1990). GIMS began as a vegetation modelling and fire behaviour prediction system. Subsequent additions have included more information on other factors, GIS links and map production (Kessell, 1990). In our case, the primary requirement was a system to organize and consolidate data effectively (Table 3).

The Catchment Management System (CMS) is initially being developed for the mountain catchments of the Cape Province, but the design will be generic, i.e. it will be structured so that it can easily be adapted for use in other ecosystems (e.g. grassland catchments, afforested catchments, nature reserves or plantations) by simply changing the information in the databases and building new rule models.

6.1. CONSTRAINTS

The computer hardware available to the manager and the costs of upgrades were a significant constraint on the options for an effective system design. The optimal solution, in terms of access and use by the field manager, would be to have the full spatial database and analytical facilities available on the manager's desktop computer. This was not possible because of the limited memory (640 kb), data storage capacity (20–40 Mb), data processing speed of standard IBM AT-compatible computers (without maths co-processors) and graphics output requirements (a monochrome EGA screen is the minimum that could be used). The cost of upgrading the equipment and purchasing and licensing the necessary programmes to implement this option was also prohibitive. There is also a severe shortage of personnel with the training and skill required to maintain such a complex and widely dispersed system. The best compromise was to provide the manager with all the data except the actual spatial reference data. The spatial data will be maintained on a central geographic information system that will function as a master database for the Cape catchments. The integrity of data in the system is also ensured by providing dedicated data export and import facilities. Data will be transferred on floppy disks because many management centres do not have telephones with direct dialling.

6.2. DATABASE DESIGN

The system consists of two independent database structures, each designed with the compartment as the focal data element. The one system is designed to operate on personal computers with a DOS operating system and the other on a workstation with a UNIX operating system. Both systems have been designed to allow modifications, such as different functions and relations, to be added for different applications and to meet changing user requirements. The CMS uses pre-defined menus, windows and screen data entry and editing forms to simplify access, to minimize the amount of typing required and reduce the time required for learning how to operate it. Certain fields are made compulsory so that data required by other databases and for the applications must be supplied for the system to run correctly. Data dictionaries have been installed on both systems to provide a standard for naming conventions and a record of all the variables, with their definitions and check values, in the system.

The master system resides on a UNIX-based workstation and has been developed in the GIS package *Arc/Info* Version 6.0. A customized *Arc/Info* menu system provides the following primary options: data capture and editing, query and reporting, utilities for data analysis and a help facility. The database and data manipulation facilities have been developed and applications similar to those on the PC system will be implemented during the coming year. All the menus and facilities have been written in the form of batch files using the *Arc Macro Language* supplied with *Arc/Info.*

The DOS-based system is designed for use by the catchment managers. It has menus for data entry and editing, queries and reporting, capture and analysis of non-spatial data. Dedicated data importing and exporting menus are included to ensure that both systems maintain similar non-spatial data sets. The duplication of data on both systems also provides a passive back-up in cases where computers and data back-ups fail. The PC programmes and bar-graph routines have been written in *dBASE-IV* 1.1 programming language and compiled using the *dBASE-IV* compiler supplied with the Developer's Edition so that they function as independent programmes and the users do not need *dBASE-IV* to run the CMS.

All map data is digitized using an A0 CALCOMP 9500 series digitizer with an accuracy of 0·025 mm and conforms to the National Standard (CCNLIS, 1990). Wherever possible, maps on a polyester base are used because paper maps are not dimensionally stable. A minimum of four co-ordinate registration marks are used on each map to ensure that features are accurately located. The map features are also plotted to scale on a pen plotter so that they can be overlaid on a light table and visually checked for accurate registration on the original maps.

7. Key elements

The key elements of the system are: (1) a set of linked databases; and (2) a set of simple rule models to meet some of the needs for identifying and setting priorities for tasks when compiling year plans.

7.1. DATABASES

There are eight primary databases in the system, namely compartment, fire records, alien plant control, land tenure, monitoring, visitor records, wildflower harvesting and

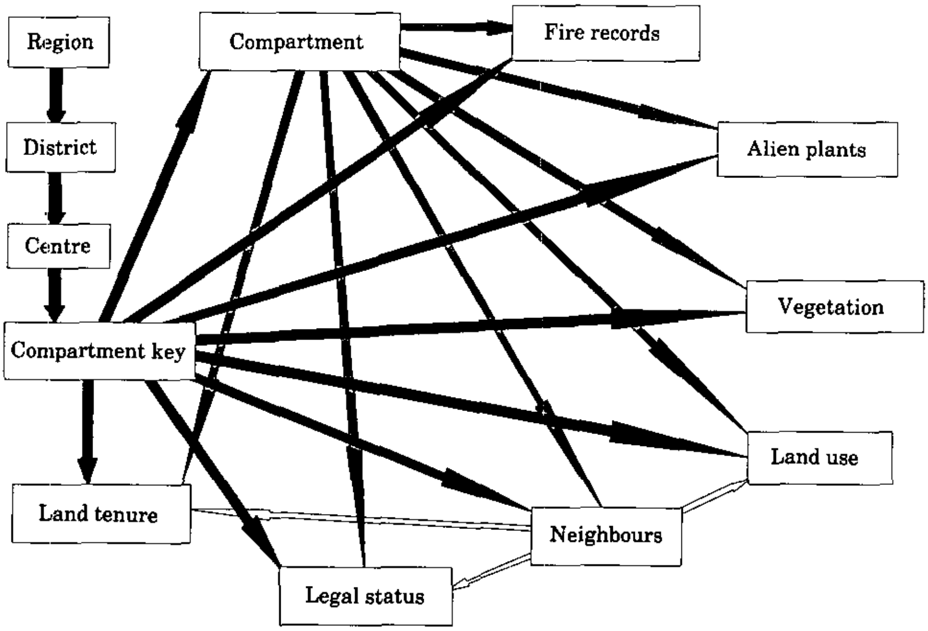

Figure 1. A simplified diagram of the Catchment Management System showing the organization of the data and the key routes of access to data. Entry begins with the management region and the calculation of the compartment key (see Section 7.1). The data editing and query options give the manager the choice of looking at databases from management compartments through to land tenure (black arrows). Selecting the compartment option provides access to the data on fire records through to land tenure (stippled arrows) for that compartment. By selecting the neighbours option information on the properties adjacent to that compartment can be obtained (hollow arrows).

legislation. The legislation, visitor and wildflower harvesting databases will be developed separately as they are not linked directly to the others and will not contain (or have links to) spatial data. The first phase of the development focused on the databases and applications involving compartment, fire, alien species, vegetation, land use, the legal status of land and land ownership (Figure 1). Only these are described here.

The spatial information is divided among five databases with distinct spatial units to accommodate the non-spatial PC system. For example, a single management compartment may contain more than one land owner's properties, a fire may burn across more than one management compartment. Each of these databases actually comprises more than one separate database internally, but this structure will not be apparent to the users as the menu system will only refer to the five key spatial databases, and all changes during editing and updating will be done using set routines.

The database structure is built around a system of key variables which identify and relate data for the same area in the different spatial map layers. The primary key is the *compartment key* (Figure 1). This is created automatically on the GIS database as the user selects the region, district, centre and compartment of interest. On the manager's system the region, district and centre are set up when the programme is installed. In the GIS structure the *compartment key* is used to provide the primary index for merging data sets when map layers (coverages) are overlaid and joined. These merged data sets are the ones that are exported to the manager's system as fixed-format text files. The data import facility is designed to take this data and place it into the correct locations in the database structure on both systems.

TABLE 4. Information contained in, or accessed via, the database for each management land unit or compartment

Basic: compartment number, size (ha), perimeter (km), legal status, zoning, land owner's name and phone number

Vegetation: vegetation type(s) names, description of the vegetation structure and proportion of compartment per vegetation type

Fire history: historical fire record and current status (table of the area of each veld type by age in years)

Alien plant information: area per species, density class and control status, presence of biocontrol agents, control history

Field observation data on fauna and flora: date, species, locality, habitat, population structure

Population survey information: species names, plot number, location, summary of past surveys and results

Special species: notes on rare, endangered and indicator species

Infrastructure information: type and maintenance history, recreation facilities, status of fencing, fire danger points

Erosion information: notes on points and sources, record of control history

Adjacent areas: legal status, land ownership (including name, telephone number), infrastructure present, land use, veld type and age

Servitudes: current (owner's name and address, type of servitude, period, annual fee) and history, existing water rights

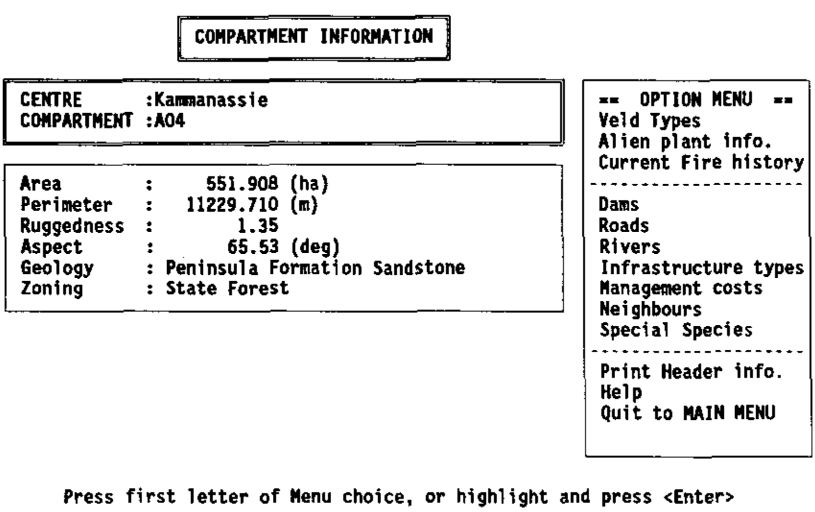

Figure 2. The compartment database screen and menu as implemented in *dBASE-IV* on the PC system.

7.1.1. *Compartment database*

This is the most complex database as it will include dynamic links to most of the other databases so that additional data for a compartment can be displayed when required (Table 4; Figure 1). The layout of the compartment data screen is shown in Figure 2.

TABLE 5. Information recorded in the fire report and fire database

Date and time when the fire began and was brought under control
The origin of the fire and the ownership of that property
The person who reported the fire
The cause: Lightning, falling rocks; honey smoking, fire-break burning, campers, farmers, vehicle, train, controlled fire, other or unknown The degree of certainty that the cause is correct (sure–unsure)
Weather observations: Date, amount and duration of the last rainfall before the fire (for planned fires) Regular observations of temperature, humidity, windspeed and direction
Fire behaviour: Observations of the fuel structure, flame lengths (metres, head or backfire), estimated rate of spread (metres per second) and controllability of the fire, preferably in conjunction with the weather readings
Estimates of the costs of the damage caused to infrastructure and personnel: e.g. buildings, vehicles, equipment, personnel injuries
Estimates of the cost of the fire or fire control operations: e.g. salaries, overtime, allowances, rations, transport, helicopters, fire-torch fuel, other items
Description: A chronological description of the course of the fire and the control operations undertaken For planned fires this would include an assessment of whether the operation went according to plan

This database is designed to replace the current compartment register. It contains current and historical data about the fires, management actions and alien plant control measures in each compartment. Provision is also made in the query and reports menu for the production of summaries of data in the compartment database.

7.1.2. *Fire records database*

Fire records can be divided into two kinds: those for deliberate, planned burning operations and those for unplanned fires. All the essential data (Table 5) is common to both so they have been developed as a single database. In the spatial database each fire is kept in a separate map data layer. The individual fire maps can then be overlaid to calculate items such as the most recent fire in a compartment and the post-fire age of the vegetation in a compartment. The design for the PC database was derived from the fire record form currently used in the Western Cape. The manager enters some of the data and the remainder is provided by the GIS once a map of the fire has been digitized (Figure 3). This facility saves the time that the manager would have spent on measuring, for example, the area of each property that was burnt.

The manager enters the data on the date and time the fire started and ended, the cause of the fire, who reported it, weather and fire behaviour observations, the costs associated with the fire and the descriptive report (Figure 3). A map of each fire is prepared with the following information (a copy is also filed in the office):

- *point of ignition (or points for prescribed burns);*

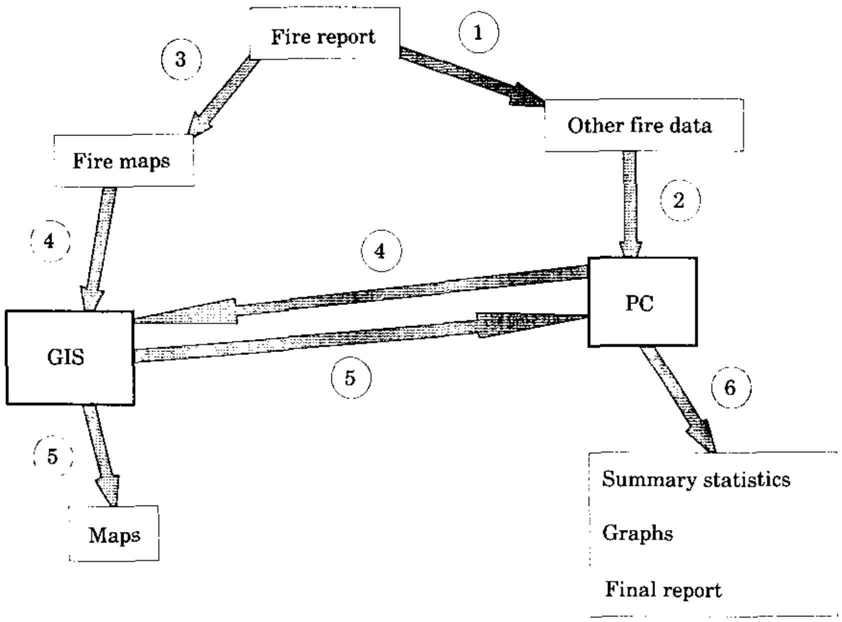

Figure 3. A simplified example of the flow of fire data to and from a manager: (1) The manager collects the data. (2) The non-spatial data (e.g. cause, costs) are entered on the PC system. (3) A map of the fire is compiled. (4) The map and the fire data on a floppy disk are posted to the operators of the GIS system who digitize the map. (5) A map of the fire and a disk with additional data from the GIS (e.g. area burnt) is sent to the manager. (6) The final report on the fire is produced.

- *fire boundaries; additional boundaries at a set time (each day for wildfires) are optional;*
- *at least four reference points for orienting and locating the map accurately, such as spot height marks or geographic coordinates;*
- *location of fire lines and counter fires is optional;*
- *location of natural boundaries of the fire is optional.*

The following spatial data for each fire is derived from the digitized map, and data in the spatial database, and produced in a format for transfer to the manager's PC system (Figure 3):

1. Data for the fire records database:

   - *location of ignition point—vegetation type, age, ownership;*
   - *statistics per vegetation type—vegetation type name, date of fire, age at the time of the fire, area burnt (ha), percentage of the total area of that vegetation type;*
   - *statistics of the area burnt divided according to land ownership, the land's legal status and land uses;*
   - *if daily fire boundaries have been drawn, the progressive area burnt each day in the fire is tabulated.*

2. Data for the compartment database:

   - *compartment number, area (ha) per vegetation type and age when burnt.*

TABLE 6. Information on the ownership of properties adjacent to the management boundaries or within a proclaimed mountain catchment area (MCA). In a proclaimed MCA the law allows the authorities to prescribe certain management actions and in some areas there are contracts with the owners for their properties to be managed by the conservation authorities

Name of property: erf name or farm name
Land owner or manager: name, address, telephone number
Legal status of land: whether the property is State Forest (or Nature Reserve) or MCA
Servitudes: extant and historical, name of owner, type of servitude, period, annual fee
Water rights: name of owner, type of water right

7.1.3. *Alien plant control database*

The alien plant database is similar to the fires database. The following information is kept about each invaded area: date of observation or map, species, density class and control treatment. In addition to this, records of the presence of biocontrol agents and a history of control operations are kept in the database. Provision is also made for observations and data on the responses of alien plants to control treatments. In the spatial database a separate map data layer is kept for each species, density class and control treatment. If an invaded area is treated then a new map layer is created with the new data. This allows the historical record to be kept in both systems. The map layers are overlaid with other data to derive information such as the time since the treatment or fire in an area. The information on the density, extent of the invaded area and control history is also accessed via the compartment database (Figure 1; Table 4).

7.1.4. *Land tenure database*

This database contains all the necessary information on all the properties within, or adjacent to, the management centre (Table 6). Some of this information is dynamically linked to the compartment database (see Table 4) and is displayed in response to specific queries.

7.1.5. *Vegetation database*

The vegetation database consists of a map data layer in the GIS of the distribution of the different vegetation types. Each has a mnemonic, a short name and a detailed description. The PC vegetation data is contained in a small database with the descriptive data and the area (ha) of each type. The vegetation types used are those supplied on the management maps unless more detailed maps are available. For example, there is a detailed floristic map of the Kogelberg State Forest in the Western Cape (Boucher, 1978). The map for the Kammanassie mountain range in the Southern Cape shows vegetation classes based on studies by Bond (1981) and subsequently refined (Seydack, 1986). These classes are based on a combination of floristics (the dominant species) and cover in the under-, mid- and overstorey (Bond, 1981; Campbell, 1985). A dominant or important species has been selected as an indicator species for each vegetation type. Data on the *Vital Attributes* (Noble and Slatyer, 1980), such as juvenile periods, seed dispersal, regeneration modes and seed bank types, are kept for each plant species in the database. The

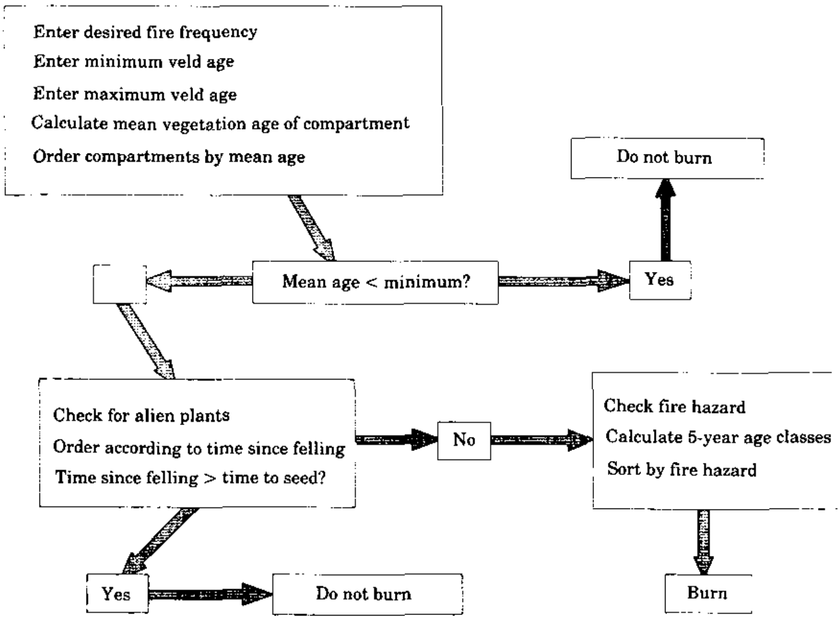

Figure 4. A diagram of the procedure for assigning priorities for the planned burning of compartments showing the rules and paths followed during its execution (see text).

data on the juvenile period of indicator species is used to determine the minimum post-fire age for burning a compartment (see Section 7.2.1; Richardson *et al.*, in prep.).

7.2. APPLICATIONS

A number of applications for data analysis and reporting have been noted in the descriptions of the databases above. The procedure for setting priorities for planned fires described here is derived from Richardson *et al.* (in prep.).

7.2.1. *Priorities for planned fires*

At the start of each fire season, managers must decide how best to allocate their limited resources towards the major task of prescribed burning while at the same time adhering to management objectives. A procedure for prioritizing compartments for burning was developed for the CMS (Figure 4). The procedure is menu driven and interactive, and derives the information required for ranking from the compartment, fire records and alien plant control databases. Spatial information is derived from the GIS. Other data are provided by the user in response to prompts. Major factors that influence the choice of compartments to burn are vegetation age, the flammability of the vegetation and the status of alien plants (Richardson and Le Maitre, 1991; Richardson *et al.*, in prep.).

Fire hazard mapping is done by identifying major structural classes in the vegetation, an approach similar to that used elsewhere (Kessel, 1990; MacLeod and Ludwig, 1991). Biomass accumulation rates, estimated for each category of vegetation structure, form the basis of the fuel models which are required as inputs for fire behaviour prediction models. The fuel models estimate the fuel conditions in each vegetation type in 3-year age classes after fire. The FIRE1 module of the BEHAVE fire behaviour prediction system (Andrews, 1986) was used to predict flame lengths (an index of fire hazard) for each fuel model using climatic conditions for a "normal" day in the fire season (see Richardson *et al.*, in prep.). The predicted flame lengths are grouped into fire hazard classes: low (0–2 m), moderate (0–4 m), high (4–7 m) and extreme (> 7 m).

The first stage of the procedure is to derive the mean vegetation age, weighted by area, for each compartment (Figure 4). This data is used to provide the first ranking and to group the compartments in age classes. Compartments with a mean age less than a specified minimum for the slowest maturing indicator species in a vegetation type in a compartment are allocated to a group which should not be burnt. Alien plants such as pines (*Pinus* spp.), *Hakea sericea* and *Acacia* spp. are fire-adapted. Fires in untreated stands result in prolific regeneration and the establishment of forests of aliens which suppress indigenous elements, and alter other ecosystem properties (Richardson *et al.*, 1992). It is essential, therefore, that a control treatment, such as the felling of the plants, is followed by a fire before the saplings mature and produce more seeds. The database is checked to see if alien plants are present and the compartments are re-sorted within age classes according to the time since a felling treatment. If the seedlings could have matured since the parent plants were felled the compartment is removed from the list of those to be burnt. The final stage is to determine the fire hazard and then reorder the compartments, within age classes and age since felling, according to the fire hazard. The procedure generates a table listing all the compartments in a management centre, ranked according to their priority for burning. Other criteria that could influence priorities (the status of indicator species, the presence of rare and endangered species, the potential damage if fires spread to adjacent areas, the water needs downstream and the state of readiness of the compartment for burning, i.e. preparation of fire breaks, etc.) are listed in the table, but are currently not used for ranking (Richardson *et al.*, in prep.).

8. Map production

One of the major advantages using a GIS is the ease with which specialized maps can be produced and updated. The GIS also enables one to overlay existing data and derive other information that is not obvious to the eye. The standard base maps used by managers are the 1:50 000 scale topographic series produced by the Directorate of Mapping and Survey, each of which covers an area of 0·25 degrees longitude by 0·25 degrees of latitude (about 200 km^2). This scale and base map system has been adopted for the CMS. These maps provide the baseline data on natural features (e.g. rivers, mountain peaks), infrastructure (e.g. roads, houses) and land use (e.g. orchards, pasture, urban areas). In addition, the managers have maps showing information such as fires, alien plants, vegetation types and land ownership boundaries, and, also, additional infrastructure which may not be evident on the standard base maps.

The most important maps required by the manager are those showing the current status of the vegetation and the alien species in the area (Table 7). These will be produced annually at the end of each fire season to make the data available for planning for the next year's activities. Maps showing the high fire hazard areas are very useful for planning managed fires to burn key areas so as to provide a mosaic of young and old vegetation, reducing the risk of fires spreading uncontrollably. Managers also consider a number of other types of mapped information when they are planning fires or creating contingency plans for areas where there is a high fire risk (Richardson and Le Maitre,

TABLE 7. Management maps which require updating annually

Vegetation age: the distribution of the different vegetation types and age classes of the vegetation
Fire history: updated fire boundaries showing the most recent fire in each area
Fire hazard: this information is derived from data on the vegetation type and age
Alien plants: the areas invaded by each species, the density class in each area and the last control operation in each area

TABLE 8. Types of mapped information considered by managers when planning management actions or required as base data for orientation when in the field

Vegetation types: as defined in the management plans and vegetation maps
Special indigenous species: localities of Red Data Book species and other unusual species
Compartment boundaries and numbers
Cadastral property boundaries: for defining property ownership
Legal status boundaries: e.g. boundaries of state, local authority and proclaimed catchment areas
Land use: a simple hierarchical classification beginning with a primary division into natural lands, transformed lands and built-up areas and townships
Natural features: e.g. rivers, springs, wetlands, waterfalls
Topographic features: contours of elevation and spot heights
Geology: lithology
Outstanding natural features: e.g. caves, waterfalls
Cultural and archaeological sites
Erosion points and sources
Permanent monitoring sites, observation localities
Man-made features: e.g. quarries, roads, paths, railways, fences, telephone and power lines
Recreation facilities: inside and outside the boundaries, hiking routes, water sources

1991; Table 8). For example, recreation sites—especially where camping and the making of open-air fires is permitted—are important fire hazard areas.

9. The future

Several facilities must still be developed. The highest priority will be given to a fully-integrated expert system to assist the manager in setting priorities for alien plant control operations, particularly where mixed stands are involved (Richardson and Le Maitre, 1991). The managers also require a database for storing and analysing information from monitoring records, including plant and animal population dynamics, specimen collections and plant community structure. Databases for visitor information and climatic data from their automatic weather stations are also important. The law enforcement officers need a database for storing and reporting on permits for wildflower harvesting.

There is also a need for a system to document relevant legislation, information on rare and endangered flora and fauna and an expert system to provide legal advice. Once the managers become accustomed to using the current system they will undoubtedly discover its limitations and identify new facilities they require.

The next area for development, once the system for the Cape catchments is fully operational, would be to look at implementing it in other catchment areas in other parts of South Africa. The same system could also be implemented in nature reserves and commercial plantations. Managers of these areas would require different kinds of information for their decisions, and planning would be based on different rules (e.g. habitat requirements of animals, silvicultural treatments for plantations).

Several fire behaviour prediction systems are available (e.g. Walker *et al.*, 1985; Kessell and Cattelino, 1985; Kessell, 1990), and some are linked to GIS map layers with terrain, fuels and climate and are able to map the predicted fire boundaries (e.g. Kessell, 1990; Zack and Minnich, 1991). A fire-spread simulation model is available as a demonstration in *Arc/Info* Version 6.0 and with some modifications that could be implemented in the CMS. This could provide managers with the opportunity to simulate fires in their areas under different conditions. It could also be used to predict the spread of wildfires, although the latter facility would be restricted to those close enough to the GIS or with a facsimile machine so that the predictions could reach them in time to be of use.

Another area for development would be the production of refined maps of the different vegetation types. Direct gradient models of vegetation distribution (see Kessell, 1979, 1990; Bergeron *et al.*, 1985) are available for some areas (e.g. Bond, 1981; Walker, 1988). A few areas have detailed floristic maps (e.g. Boucher, 1978; McDonald, 1988), but most areas lack suitable vegetation maps. A GIS provides the data processing and analytical facilities to complement both approaches. The gradient models can be turned into maps because the factors underlying the vegetation gradient can be classified and mapped. These maps can then be checked and refined by field surveys (Kessel, 1990; Moore *et al.*, 1991). The gradients underlying detailed floristic maps can also be derived by overlaying the vegetation on maps of environmental factors such as geology, slope, aspect and rainfall. The data produced during this process can then be used to generate gradient models for testing and refinement (Moore *et al.*, 1991). Both these approaches can be used to provide first approximations, at least of vegetation structure, for adjacent and other similar areas. The same process can also be used with data on rare species localities. Likely sites for additional populations can be identified and mapped for subsequent field surveys.

GIS systems have fully-integrated spatial topology, but the possibility of developing the equivalent of spatial topology for the time dimension (Vrana, 1989) provides new possibilities for analysing data on changes over time. One example would be to analyse changes in fire patterns, rather than simply fire size or cause, before and after the implementation of a *natural burning* system. The same applies to changes in land use patterns. A system like the CMS can never replace the manager, solve all the problems or meet all the information needs. However, by placing the essential data at his fingertips, it assists him to make informed and sound decisions and plan far more rapidly and efficiently.

The development of the Catchment Management System was funded by the South African Department of Environment Affairs. We thank the Chief Directorate of Nature and Environmental Conservation (CDNEC) for actively assisting and supporting us in our surveys and with the data we have used to develop and test the system. Management staff in the CDNEC and members of the Steering Committee helped to initiate this work and have provided valuable comments and suggestions during the development. S. Hine and A. C. Duckworth (GIMS Pty, Ltd) and K. B. Higgins have assisted with the system design and are responsible for programming the database systems. We thank G. G. Forsyth, C. A. Jones, L. Cunningham and D. McKelly for their help in getting the data into the system.

References

Andrews, P. L. (1986). *BEHAVE: Fire Behaviour Prediction and Fuel Modelling Subsystem—BURN Subsystem*. General Technical Report INT-194. USDA Forest Service.

Anon. (1990). *Policy on National Environmental Management System*. Cape Town, South Africa: Cape Provincial Administration Chief Directorate Nature and Environmental Conservation.

Bergeron, Y., Bouchard, A. and Massicotte, G. (1985). Gradient analysis in assessing differences in community pattern of three adjacent sectors within Abitibi, Quebec. *Vegetatio* **64**, 55–65.

Bond, W. J. (1980). Fire and senescent fynbos in the Swartberg, Southern Cape. *South African Forestry Journal* **114**, 68–74.

Bond, W. J. (1981). Vegetation gradients in the southern Cape mountains. M.Sc. thesis. Botany Department, University of Cape Town.

Bond, W. J. (1984). Fire survival of Cape Proteaceae—influence of fire season and seed predators. *Vegetatio* **56**, 65–74.

Bond, W. J. (1990). Describing and conserving biotic diversity. In *Biotic Diversity in Southern Africa: Concepts and Conservation* (B. J. Huntley, ed.), pp. 2–18. Cape Town: Oxford University Press.

Bosch, J. M., van Wilgen, B. W. and Bands, D. P. (1986). A model for comparing water yield from fynbos catchments burnt at different intervals. *Water SA* **12**, 191–196.

Boucher, C. (1978). Cape Hangklip area. 2. The vegetation. *Bothalia* **12**, 455–497.

Brinkman, R. P. (1990). Advanced forest planning in the Otways. *Australian Forestry* **53**, 290–294.

Campbell, B. M. (1983). Montane plant environments in the Fynbos Biome. *Bothalia* **14**, 283–298.

Campbell, B. M. (1985). A classification of the mountain vegetation of the Fynbos Biome. *Memoirs of the Botanical Survey of South Africa* **50**, 1–119.

CCNLIS. (1990). *The Standard for Data for the National Land Information System. Standards Committee of the Co-ordinating Committee for the National Land Information System.* CCNLIS Publication No. 2, Version 1. Cape Town: National Land Information Services, Chief Directorate: Surveys and Information.

Cowling, R. M. (1984). A syntaxonomic and synecological study in the Humansdorp region of the Fynbos Biome. *Bothalia* **15**, 175–227.

Cowling, R. M. and Holmes, P. M. (1992). Flora and vegetation. In *The Ecology of Fynbos—Nutrients, Fire and Diversity* (R. M. Cowling, ed.), pp. 23–61. Cape Town, South Africa: Oxford University Press.

Cowling, R. M. and Gxaba, T. (1990). Variation in post-fire recruitment of a fynbos overstorey shrub: effects on understorey community structure and implications for community-wide species richness. *South African Journal of Ecology* **1**, 1–7.

Davis, F. W. and Dozier, J. (1990). Information analysis of a spatial database for ecological land classification. *Photogrammetric Engineering and Remote Sensing* **56**, 605–613.

Deacon, H. J. (1992). Human settlement. In *The Ecology of Fynbos—Nutrients, Fire and Diversity* (R. M. Cowling, ed.), pp. 260–270. Cape Town, South Africa: Oxford University Press.

Deacon, H. J., Jury, M. R. and Ellis, F. (1992). Selective regime and time. In *The Ecology of Fynbos—Nutrients, Fire and Diversity* (R. M. Cowling, ed.), pp. 6–22. Cape Town, South Africa: Oxford University Press.

Edwards, D. (1984). Fire regimes in the biomes of South Africa. In *Ecological Effects of Fire in South African Ecosystems* (P. DeV. Booysen and N. M. Tainton, eds), pp. 19–37. Berlin: Springer-Verlag.

Folse, L. J., Mueller, H. E. and Whittaker, A. D. (1990). Object-oriented simulation and geographic information systems. *AI Applications* **4**, 41–47.

Hoffmann, M. T., Barr, G. D. and Cowling, R. M. (1990). Vegetation dynamics in the semi-arid eastern Karoo, South Africa: the effect of seasonal rainfall and competition on grass and shrub basal cover. *South African Journal of Science* **86**, 462–463.

Kessell, S. R. (1979). *Gradient Modeling: Resource and Fire Management*. New York: Springer-Verlag.

Kessell, S. R. (1990). An Australian geographical information and modelling system for natural area management. *International Journal of Geographical Information Systems* **4**, 333–362.

Kessell, S. R. and Cattelino, P. J. (1978). Evaluation of a fire behaviour information integration system for southern California chaparral wildlands. *Environmental Management* **2**, 135–139.

Kruger, F. J. (1979). South African heathlands. In *Heathlands and Related Shrublands—Descriptive Studies* (R. L. Specht, ed.), pp. 19–80. Amsterdam: Elsevier.

Le Maitre, D. C. (1992). The relative advantages of seeding and sprouting in fire-prone environments: a comparison of life histories of *Protea neriifolia* and *Protea nitida*. In *Fire in South African Mountain*

Fynbos: Ecosystem, Community and Species Response to Fire at Swartboskloof (B. W. van Wilgen, D. M. Richardson, F. J. Kruger and H. J. van Hensbergen, eds), pp. 123–144. Berlin: Springer-Verlag.

Le Maitre, D. C. and Midgley, J. J. (1992). Plant reproductive ecology. In *The Ecology of Fynbos—Nutrients, Fire and Diversity* (R. M. Cowling, ed.), pp. 135–174. Cape Town, South Africa: Oxford University Press.

MacLeod, N. D. and Ludwig, J. A. (1991). Using BURNECON to evaluate the economics of fire management in semi-arid woodlands, eastern Australia. *Journal of Environmental Management* **33**, 67–67.

McDonald, D. J. (1988). A synopsis of the plant communities of Swartboskloof, Jonkershoek, Cape Province. *Bothalia* **18**, 233–260.

Moore, D. M., Lees, B. G. and Davey, S. M. (1991). A new method for predicting vegetation distributions using decision tree analysis in a geographic information system. *Environmental Management* **15**, 59–71.

Nobel, I. R. and Slatyer, R. O. (1980). The use of vital attributes to predict successional changes in plant communities subject to recurrent disturbance. *Vegetatio* **43**, 5–21.

Rebelo, A. G. (1992). Preservation of biotic diversity. In *The Ecology of Fynbos—Nutrients, Fire and Diversity* (R. M. Cowling, ed.), pp. 309–344. Cape Town, South Africa: Oxford University Press.

Richardson, D. M. and Le Maitre, D. C. (1991). *The Cape Catchments Management System: Report on a Survey of User's Requirements.* Pretoria: Division of Forest Science and Technology, CSIR.

Richardson, D. M., Macdonald, I. A. W., Holmes, P. M. and Cowling, R. M. (1992). Plant and animal invasions. In *The Ecology of Fynbos—Nutrients, Fire and Diversity* (R. M. Cowling, ed.), pp. 271–308. Cape Town, South Africa: Oxford University Press.

Richardson, D. M., van Wilgen, B. W., Le Maitre, D. D. and Higgins, K. B. (in prep.) Using computer technology in fire management: an example from the mountain catchment areas of the Cape Province, South Africa. *International Journal of Wildland Fire.*

Seydack, A. H. W. (1986). *Regional Policy Memorandum for Southern Cape and Tsitsikamma Mountain Catchment Areas.* Pretoria: Department of Environment Affairs, Forestry Branch.

Seydack, A. H. W., Van Daalen, J. C., Van Dijk, D., Reynell, D., Heyns, H., Jooste, A., Ferguson, M., Pitchford, W., Durrheim, G. and Willems, D. (1990). Yield regulation in the Knysna forests. *South African Forestry Journal* **152**, 50–61.

Specht, R. L. and Moll, E. J. (1983). Mediterranean-type heathlands and shrublands of the world: an overview. In *Mediterranean-Type Ecosystems—the Role of Nutrients* (F. J. Kruger, Mitchell, D. T. and J. U. M. Jarvis, eds), pp. 41–65. Berlin: Springer-Verlag.

Van der Zel, D. W. and Walker, B. H. (1988). Mountain catchment management with goal programming. *Journal of Environmental Management* **33**, 65–77.

Van Wilgen, B. W. (1981). Some effects of fire frequency on fynbos plant community composition and structure at Jonkershoek, Stellenbosch. *South African Forestry Journal* **118**, 42–55.

Van Wilgen, B. W. (1984). Fire climates in the southern and western Cape and their potential use in fire control and management. *South African Journal of Science* **80**, 358–362.

Van Wilgen, B. W. and Viviers, M. (1985). The effect of season of fire on serotinous Proteaceae in the western Capé and the implications for fynbos management. *South African Forestry Journal* **133**, 49–53.

Van Wilgen, B. W., Higgins, K. B. and Bellstedt, D. U. (1990). The role of vegetation structure and fuel chemistry in excluding fire from forest patches in the fire-prone fynbos shrublands of South Africa. *Journal of Ecology* **78**, 210–222.

Van Wilgen, B. W., Everson, C. S. and Trollope, W. S. W. (1991). Fire management in southern Africa: some examples of current objectives, practices and problems. In *Fire in the Tropical Biota* (J. G. Goldhammer, ed.), pp. 179–215. Berlin: Springer-Verlag.

Van Wilgen, B. W., Bond, W. J. and Richardson, D. M. (1992). Ecosystem management. In *The Ecology of Fynbos—Nutrients, Fire and Diversity* (R. M. Cowling, ed.), pp. 345–371. Cape Town, South Africa: Oxford University Press.

Van Wyk, D. B. (1987). Some effects of afforestation on streamflow in the Western Cape Province, South Africa. *Water SA* **13**, 31–36.

Vrana, R. (1989). Historical data as an explicit component of land information systems. *International Journal of Geographical Information Systems* **3**, 33–49.

Walker, J., Davis, J. R. and Gill, A. M. (1985). *Towards an Expert System for Fire Management at Kakadu National Park.* Technical Memorandum 85/2: 1–169. Canberra: Institute of Biological Resources, CSIRO.

Walker, R. S. (1988). A gradient analysis of grassed mountain catchments in the Natal Drakensberg. *Journal of the Grassland Society of South Africa* **5**, 179–185.

Wicht, C. L. (1945). *Report of the Committee on the Preservation of the Vegetation of the South Western Cape.* Cape Town: special publication of the Royal Society of South Africa, Royal Society.

Wilson, P. A. S. (1985). *General Policy Memorandum for the Management of Mountain Catchments in the Western Cape Forest Region.* Pretoria: Department of Environment Affairs.

Yeaton, R. I. and Esler, K. J. (1990). The dynamics of succulent karoo vegetation. *Vegetatio* **88**, 103–113.

Zack, J. A. and Minnich, R. A. (1991). Integration of geographic information systems with a diagnostic wind field model for fire management. *Forest Science* **37**, 560–573.