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The changing role of remote sensing for land resource assessment in Scotland: lessons for the future

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Abstract

The paper explores the changing role of remote sensing within land resource assessment applications in Scotland over the past 60 years. The objective is to identify key trends and highlight future directions. A wide definition of remote sensing (RS) and resource assessment is adopted, the latter including both tangibles like soils, vegetation and land cover but also intangibles like the visual landscape. The historical period is reviewed in terms of three distinct eras. Firstly, the **manual era**, during which all mapping and cartography was done by hand. This is illustrated using the Soil Survey of Scotland where RS was essentially used as a support to field mapping techniques. The second era concerns the **transition to the digital**, where we still used conventional air photo interpretation but combined it with digital mapping. This is illustrated using the Land Cover of Scotland (1988) database, where RS data were used as the primary data source. The third era is the present, the **era of the integrated data model**. Here we are using RS, particularly in the landscape arena, to support both quantitative landscape analysis and to enable user participation. Each of the illustrative case studies is set out in terms of its relevance to contemporary Government policy (*e.g.* agriculture, environment, renewable energy) and its cost. Irrespective of their technological contexts (*i.e.* analogue or digital), these case studies represent significant operational uses of RS and a number of themes emerge: i) the changing role of RS data from intermediate source of information (where they were discarded afterwards) to RS data being both a source and a key part of an integrated database; ii) the degree to which users were involved in developing the applications: from the Soil Survey which was essentially scientist-led, to the mixed model of the

LCS88, and towards the current model where the users are very much involved in the specification and development of the information products; iii) the visibility of the data to the users. In the past, users were generally unaware that RS data were fundamental to the production of the information product because they did not see it. Now, in the era of fused databases, the role of RS is much more apparent. The paper concludes by setting out some of the new opportunities for RS data sources, analysis and applications to resource assessment.

Key words: remote sensing, resource assessment, soil survey, land cover, landscape, virtual reality

1. Introduction

This paper provides a review of the past 60 years of research and operational uses of remote sensing for land resource assessment in Scotland. It is principally concerned with the work of the Macaulay Institute but the aim is to highlight, using a set of case studies, significant changes in policy drivers (*e.g.* in agriculture and environment), in resource assessment methodologies, and in the role of users. These changes have wider relevance in terms of our understanding of the critical importance of remotely sensed data to contemporary society, especially its role in integrated data infrastructures and user interactions with such data, both now and in the future.

In this paper we adopt a broad definition of 'remote sensing' (RS) which includes aerial and satellite platforms, and a range of passive and active instrumentation. Because of our historical perspective, much of the review is actually concerned with research and applications based upon the use of aerial photography. However, examples of land resource assessments using Landsat TM, AVHRR and SAR data are also included. It is also important to be aware that, in using the term ‘resource assessment’, we mean both the assessment of tangible land resources (*e.g.* soils, vegetation and land cover), which are constructs familiar to the scientific community, and less tangible ones such as the visual landscape, which are often more familiar to the general public.

The paper is developed upon a historical perspective and is structured accordingly. The historical period is reviewed in terms of three distinct eras. Firstly, the **manual era** (broadly 1938-1984), during which all resource mapping and cartography were done manually. This is illustrated using the Soil Survey of Scotland where RS was essentially used as a support to field mapping techniques. The second era concerns the **transition to the digital** (broadly 1985-1995), where we still used conventional air photo interpretation but combined it with digital mapping. This is illustrated using the Land Cover of Scotland (1988) database, where RS data were used as the primary data source. The third era is the present, the **era of the integrated data model and decision support tools** (broadly 1995 onwards). Here, we are using RS, particularly in the landscape arena, to support both quantitative landscape analysis and to enable user participation. Each of the illustrative case studies is set out in terms of its relevance to contemporary Government policy (*e.g.* agriculture, environment, renewable energy) and its estimated cost. The final part of the paper deals with contemporary research issues and the identification of potential new opportunities for the application of RS in land resource assessment.

2. The manual era (1938-1984): the soil survey of Scotland

For most of us, it is hard to imagine now the detailed circumstances that prevailed in the UK during the 1930s. However, it is possible to isolate some factors that might have shaped the contemporary ‘world view’ (Birnie *et al.*, 2002). With memories of the Great War still fresh, the rigours of the Depression ongoing, and an awareness of the likelihood of further unrest in continental Europe, it is possible to understand why there was a clear agenda for making better use of the country’s land resources. Soil and soil improvement were seen as being fundamental to improving agricultural productivity (epitomised in the slogan ‘food from our own resources’) and as a result, soil survey and land classification were regarded by some as key to improved planning of land utilisation (Grant, 1990). At the same time, significant progress was being made in methods for mapping soils, particularly in the USA and Canada. It is therefore possible to trace through the 1930s a growing interest in a survey of soils within the UK, marked by events such as the setting up of a Soils Correlation Committee in 1930, a Soil Survey Executive Committee in 1936, and culminating with the formal establishment of the Soil Survey of Scotland in 1938 and the Soil Survey of England and Wales in 1939.

WWII added further impetus to the need for a comprehensive programme of soil survey within the UK, and in 1946 the Agricultural Research Council appointed a Soil Survey Research Board to be responsible for the overall scientific supervision of this work. Interestingly, the Board included not only senior technical staff but also a ‘representative’ of the government agriculture department in Scotland, which funded the Scottish component of the survey.

One of the Board's first decisions was that coloured soil survey maps should be published at a scale of 1 inch to 1 mile (1:63,360), which was based upon the Geological Survey map series, for which the field mapping base was 2.5 inches to the mile (1:25,000). This decision effectively determined both the methodology for the survey and also a timescale for obtaining coverage for the whole country. In a Scottish context, the surveying technique was based upon field mapping supported by the digging, description and classification of soil pits, there being "no superior way of becoming intimately acquainted with a soil"! Thus, the standard tool of the trade was a "sharpened, pointed garden spade" (Grant, *op cit*). Until the 1960s, the soil boundaries were captured largely on 1:25 000 paper 'field sheets'.

This field-based approach, though time intensive, meant that the Soil Survey team, through experience of interpreting soils from digging pits and 'reading the landscape' (itself a form of RS), was developing both a comprehensive knowledge of soil/landform/vegetation relationships in rural Scotland, and an ability to capture these on the soil maps. By 1972, the 25th anniversary of the Soil Survey Research Board, the Soil Survey of Scotland had a team of 17 field surveyors supported by a further 11 staff including 3 cartographers, 28 people in total, plus a fleet of 4x4 vehicles, equivalent to an annual cost well in excess of £1 million (at today's prices). By this time they had published 20 1:63, 360 scale soil maps covering 8700 square miles (22500 sq km) with a further 2000 square miles (5200 sq km) completed, amounting to about one-third of the area of Scotland. This area corresponded to most of the improved agricultural land, reflecting the agricultural focus of the Survey's sponsors, but the inescapable fact was that, at this rate of progress and given the same resources, it would take another 50 years and a further £50 million to map the whole country at this scale! Clearly this timescale was incompatible with the original notion of having national soil map coverage to assist in land use planning, and the world of the 1970s was a very different one to that of the 1930s when the soil mapping project was conceived. There was clearly a very long delay between having the need, and having the need satisfied!

So where does remote sensing fit into the history of the Soil Survey of Scotland? In 1946, when the Board set out its requirements, no extensive coverage of Scotland by aerial photography existed. However, during the 1950s, the aerial photography obtained by the RAF post-1945 became available from the Air Photograph Library of the Scottish Development Department. Despite problems of variable quality, these photographs proved “invaluable in hill areas where the base maps lacked topographic detail”.

Increasingly the soil surveyors began to use air photographs in the field, both as a base map and as a guide to delineating the boundaries of soil units, and in the undertaking of specialised surveys (e.g. of the island of Rhum in 1958). In 1960, the Soil Survey of Scotland provided a demonstration of the use of air photos as an aid to soil survey at the Royal Society of Edinburgh, and one of the Survey team attended a course in air photo interpretation at the International Training Centre in Delft, Holland. By 1964, with the introduction of the Zeiss Sketchmaster for transferring soil boundaries from photos to base maps, it was apparent that remotely sensed data were becoming increasingly embedded within the routine activities of the Soil Survey of Scotland.

From the above it can be seen that by the mid-1970s, not only were surveyors from the Soil Survey of Scotland routinely using aerial photography as a means of supporting their field mapping, but there was also a growing concern about the need to complete the national soils coverage. In particular, the principal funding body for the Survey, the then Department of Agriculture and Fisheries for Scotland (DAFS), had, via several of its technical groups and working parties, identified a pressing need for a series of soil maps that covered the whole of Scotland at a consistent scale. As a consequence, in June 1978 the DAFS issued a formal request for the Soil Survey to implement a scheme for a rapid survey (by 1981) of the remaining un-surveyed areas. This would enable the provision of a set of 7, 1:250, 000, map sheets covering the whole of Scotland (Macaulay Institute for Soil Research, 1983), and also the derivation of corresponding maps that showed land capability for agriculture (Bibby *et al.,* 1982; Bibby, 1987). This short time scale required a significant change in the mapping methodology employed. The previous approach had been based upon a field survey which was supported by air photographs, but now the approach was to be based upon air photographic interpretation with some limited ground checking. The survey was based upon pre-existing Ordnance Survey (OS) photography, which was of scales between 1:25,000 and 1:27,000, and was successfully completed and launched in 1983.

Acknowledging the differences in scale of the soil maps, it is still a remarkable fact that, whilst it had taken 25 years to map a third of the area of Scotland, it took only five years to map the entire country at the smaller scale. This would appear to indicate that all soils could have been mapped by air photo interpretation alone. However, it is important to acknowledge two critical points. Firstly, the accurate interpretation of soil boundaries from aerial photography still depended on experts with significant experience of mapping soil/landform relationships in the field. Secondly, undertaking the 1:250,000 survey, the surveyors were predominantly working in semi-natural landscapes where the relationships between soils and vegetation were relatively undisturbed by cultivation. These relationships could, therefore, be more easily interpreted directly from aerial photographs than in lowland settings, where removal of natural vegetation and the cultivation of land, masks some of the inherent differences between different soils. Aerial photographs were found to be much less useful in these situations and more ground truthing was still required. This experience highlights both the importance of expert knowledge, and an awareness of the extent to which land resource information can be directly interpreted from RS data. The Soil Survey of Scotland shows that the use of RS data is highly context-dependent, and part of the skill of the expert is their awareness of this limitation (*i.e.* where, and where not, to use RS).

There are other lessons that we can draw from the case study of the Soil Survey of Scotland. Over the period 1938-1984, remote sensing data developed from being the ancillary source to that of the principal source of information for soil resource assessment. Further, post-1970 the availability of a national coverage of aerial photography enabled a programme of much more rapid resource assessment to be rolled out, albeit at a smaller mapping scale. The shift to the 1:250,000 mapping also reflected a willingness to respond to end-user needs and a step towards the production of ‘information products’ as opposed to basic maps of soils which required expert knowledge to interpret. The concept of information products tailored to user needs heralded a significant change in our approach to resource mapping, that of more closely involving end-users in the definition of information products. Note however the critical value of having, in the first instance, national soil map coverage and associated attributes. This is reflected in the wide range of products that have since been derived from this source, such as: soil erosion risk (Lilly *et al.*, 2002); nitrate vulnerable zones (Lilly *et al.*, 2001); and potential for native woodland restoration (Towers *et al.*, 2002).

3. Transition to the digital (1985-1995): the land cover survey of Scotland

The world of the 1980s was very different to that of the 1930s. The growing awareness of environmental pollution and global change had led to increasing social commitment to a new environmental world view (Dunlap and Van Liere, 1978; Arcury and Christianson, 1990). In Scotland, the contest between the productivist and the emerging environmentalist agendas was marked by a series of high profile conflicts, which were epitomised by the campaign against investment-driven forestry in the Flow Country of Caithness and Sutherland (Avery and Leslie, 1990). The political importance of this growing environmental awareness is perhaps best illustrated by the relative number of members of environmental groups in Scotland which stood at 377,000 in 2001 compared to the membership of the National Farmers Union of Scotland (NFUS) which stood at 10,700 (or less than 3% of that of the environmental groups) at the equivalent time (Warren, 2002). These conflicts tended to highlight the fact that, whilst we had a considerable body of data relating to the productivist constructions of ‘land resources’ (which were principally to do with production-related qualities, *i.e.* market goods), we had comparatively less information of relevance to the new environmentalist-driven constructions of ‘land resources’ (which are principally concerned with qualities related to the ability to provide environmental goods and services, *i.e.* non-market goods).

During the early 1980s, there was increasing concern about this lack of relevant evidence on the nature and rate of habitat losses in the British countryside. Concerns about the loss of iconic landscape features like hedgerows had entered the political debate and were translated into a number of departmental and research organisation initiatives aimed at providing relevant data. Principal amongst these were the DOE/ITE Countryside Surveys (Haines-Young *et al.*, 2000) and the NCC (latterly SNH) National Countryside Monitoring Scheme (NCMS) (Tudor *et al.*, 1994). These national surveys were largely based around a sampling approach which enabled detailed local surveys to be extrapolated using some national scheme of land classification. While recognising the merits of this approach, the Scottish Office decided, on the basis of an expert review (Coppock and Kirby, 1987), that a complete census approach would be more appropriate in Scotland. Given the comparatively limited amount of information about semi-natural habitats, it was decided to focus on providing information on this type of land cover.

In May 1987, the Scottish Office announced the decision to produce the first detailed census of the land cover of Scotland (LCS88), funded jointly between a number of Scottish Office departments and agencies, and the Forestry Commission. The aim of LCS88 was to provide objective baseline information on which to base future countryside policy. Accordingly, whilst elements of the work were conducted by individual contractors, the whole project was overseen by a steering group chaired by a senior civil servant from the Scottish Office Environment Department and with membership drawn from all the sponsoring bodies. Every stage of the project life cycle, from data source to data base, was therefore influenced by the sponsors and their requirements. As a result of the consultants' report (Coppock and Kirby, *op cit*), the Scottish Office opted for a land cover mapping approach based upon the interpretation of specially-flown aerial photography (1:24,000). Most of this coverage comprised black and white photography, with colour photography for the Central Belt of Scotland. Acquiring this specially commissioned photography ensured that there was as little asynchrony in the land cover source information as was practicable. Whilst a number of options were considered for doing the interpretation, the contract was awarded to a team from the Macaulay Institute. This was based upon cost-competitiveness and the combined availability of expert air photo interpreters and researchers with experience in the comparatively new fields of digital mapping and GIS.

A full description of the methodology employed in the LCS88 survey is available elsewhere (MLURI, 1993) and only elements of it are highlighted here. The project was entirely RS-based, depending as it did upon the interpretation of the specially commissioned aerial photography. However, it was conceived at a time of rapid change in terms of the increasing availability of low-cost digital mapping and GIS technologies. The survey methodology therefore represents an example of a hybrid between the previous manual approaches and the emerging digital approaches to resource mapping. A key point is that, at that time (1987), the Macaulay Institute had evolved a new vision of the product from the LCS88 survey: it would be a **land cover database and not just a map**. Knowledge and documentation of the accuracy, reliability and production process of this database was recognised as a critical element of the final product. Accordingly, an integral part of the LCS88 project was the inclusion of a team of statisticians who designed a robust approach to its accuracy assessment (Buckland and Elston, 1994) based on field validation procedures.

The area of Scotland (78,000 km^2), mapping scale (1:25,000), number of hard copy air photos (15,000), size of the interpretation team (11) and the lack of low cost on-screen digitising technology all worked against a totally digital mapping solution at that time. Accordingly, a hybrid approach was adopted. This involved the interpreters following the same approach to air photo interpretation as they had used for the Soil Survey of Scotland but with a bespoke land cover classification system/interpretation key. They then manually transferred their interpreted land cover boundaries to 1:25,000 OS Pathfinder Series basemaps using Sketchmasters. Thereafter, all the steps were aimed at converting the information on these basemaps into a national land cover database. This involved a set of four PC-hosted digitising workstations where the basemap polygon, line and point information was manually digitised. At that time, the data handling tools for map digitising had not been extensively developed and there was a great deal of experimentation with software packages until we were able to create a stable version of the land cover database in ARC Info. Including the acquisition of the aerial photography, the total cost of the LCS88 survey was around £1.2M.

The Land Cover of Scotland (1988) survey represented a number of firsts. It was initiated by a set of policy customers and involved dialogue with them throughout; the methodology was based upon the marriage of conventional methods of air photo interpretation and new concepts of GIS and spatial databasing. The objective was to create a flexible database with tools to enable multiple re-use of the data in other applications. The value of this flexibility has been borne out by the wide range of applications to which the land cover data, often in association with the soils data already described, have been applied both by its funding bodies and by the Macaulay Institute (*e.g.* Hester *et al.* (1996); Towers and Horne (1997), Towers *et al.* (2001)) which was highlighted in the critical evaluation of the project by Dunn *et al.* (1995).

Despite the degree to which the data have been used since, the LCS88 still only represented a step along the way both as far as the transparency of RS data to the users is concerned, and in terms of its potential usefulness to them. Because the original material was hard copy aerial photographs, the project still adopted the 'use and lose' approach to the source RS data. Thus, the potentially valuable comparison between the source imagery and the derived information was still not possible. This means that users neither have the opportunity to directly compare the interpretation with the source imagery, nor do they have the opportunity to derive alternative interpretations: the LCS88 data represents only one potential realisation of the land cover of Scotland. Thus, although the LCS88 represents an important step away from the traditional resource survey map product, there were still a number of conceptual and technical barriers to be broken before a fully integrated land resource database could be created. Nonetheless, the LCS88 can be held up as the first significant step towards the creation of an integrated land resource database for Scotland, which, taken together with the growing availability of digital topographic mapping from the OS, and other thematic data, has enabled us to conceive a more fully integrated data model.

4. Towards the integrated data model and decision support tools (1995 onwards): landscape analysis and the renewable energy debate

Due to the increasing adoption of the environmentalist world view, the ways in which we interpret the term “land resources” have continued to widen during the 1990s. It is pointed out above that “land resources” may have both productive and non-productive meanings and this may lead to contestation and conflict. Nowhere is this presently more evident in the UK than in the arena of the government’s energy policy, particularly the generation of electricity from on-shore wind power.

Until the 1990s, wind power was neither controversial nor high profile in the British Isles. Now it is both, a consequence of policies which promote renewable energy generally and wind power specifically due to its cost competitiveness (Birnie *et al.*, 1999; Warren *et al.*, submitted). This is a response to the international consensus that climate change poses serious threats (Hasselmann *et al.*, 2003; Watson, 2003), and the resulting Kyoto Protocol, ratified by the EU in 2002. The UK, Scottish and Irish governments are all actively promoting renewable energy as part of their stated goal of achieving low carbon economies (Connor, 2003). All have adopted ambitious targets and have introduced a range of market mechanisms to facilitate their achievement. However, the continued development of wind energy will depend not only on economics but also on public acceptance. As wind power developments have accelerated, so opposition has become more vocal and resistance is chiefly a reaction to their visual impact on the landscape (Lovelock, 2004).

This situation has meant that there is a critical need for tools which assist in the strategic planning of wind farms, and also tools which have a role in conflict resolution. All wind energy developments require planning permission and therefore negotiate the planning process. In Scotland, for developments of under 50MW, the relevant planning authority is the local authority in which the development will take place. For developments over 50MW, the authority reverts to the Scottish Executive under section 36 of the existing Electricity Act.

Renewable electricity generation presents local and national planning authorities with a set of new challenges where national interests in energy security, nature conservation and national security often come into conflict with each other and also local community interests. Because of the rapidity of the policy changes towards promotion of renewable electricity, both national and local planning authorities have been left in a 'planning vacuum' (Birnie *et al.*, 1999) with no overall strategic framework from government to provide locational guidance on site suitability for wind farm developments, although, in Scotland, Scottish Natural Heritage have published strategic locational guidance for onshore wind farms, with a perspective of natural heritage issues (Scottish Natural Heritage, 2002).

This lack of strategic planning tools, such as that for assessing the capability and potential impacts of wind turbines, has led to research by the Macaulay Institute, in collaboration with the Countryside Council for Wales and Scottish Natural Heritage, to develop GIS-based tools for strategic planning (*i.e.* revealing the potential significance of different physical or policy related factors). These tools have been designed to guide stakeholders as to the issues likely to require consideration when undertaking a search for sites suitable for windfarms.

These tools require data on current land use and cover (*e.g.* type of agricultural activity, forestry, settlements), and derivations from these data (*e.g.* proximity to the road or rail network) and other spatially expressed surrogates for factors of relevance to the planning guidelines (*e.g.* visibility from long distance footpaths). The LCS88 dataset has provided source data for this tool in Scotland, and the Land Cover of Great Britain for use in Wales.

As such tools are for strategic and operational use by commercial companies, local authorities and other relevant organisations, the underlying data requires to be accompanied with accessible information regarding its accuracy, reliability and currency. The work by Comber *et al.* (2004) illustrates the importance of access to such information. Such metadata are a core element of the LCS88 dataset and have been of increasing importance in the development and submission of materials for public use (*e.g.* public planning enquiries). As with many spatial datasets compiled prior to digital data capture or storage, much of the equivalent qualitative information exists for the soils data for Scotland, and access to this, and explanation of the content and interpretation of the data, is a high priority within organisations such as the Macaulay Institute under a commitment to knowledge transfer of science and information about Scotland's natural heritage to audiences that are not only comprised of researchers. To this end, a WWW site has been developed 'Exploring Scotland' (www.macaulay.ac.uk/explorescotland/) to enhance access and understanding of basic data, and from which added value may be derived.

The second area of development concerns the provision of tools which are aimed at directly aiding the planning process by informing the various stakeholders of issues associated with site selection and planning. This requires both knowledge of participatory processes and the adoption of technologies that are credible. The objective is to assist individuals and groups to understand the function of developments, explore the potential impacts and support facilitation of discussion on methods for their mitigation. These technologies are increasingly based around the fusion of RS and virtual reality (VR) technologies.

The research seeks to improve means of enabling engagement of stakeholders in issues of landscape planning and raises the level of equity people have in decisions that have a direct affect upon their local environment and lifestyle (O'Neill and Spash, 2000; De Marchi and Ravetz, 2001). The use of VR technology, and supporting models, has been tested at public events designed to raise debate with respect to the development of wind turbines or seek local views on proposals for changing land use from agricultural activities to semi-natural woodlands, with the aim of improving the level of biodiversity in the area.

The models provided a mechanism for triggering public discussion and eliciting qualitative evidence about the use of woodlands, presence of turbines and the content of landscape views. Evaluation of the qualitative responses to the models suggests that members of the public, and those from relevant professions, have a good level of acceptance of both the means and the content of the models being used. Reasons given include evidence of time being invested in the evaluation of options at the sites of public interest (*i.e*. ‘their site’), an introduction to new technology, and a credible basis for their engagement in the management of change. Further responses towards the landscape models suggest that reactions towards the usability of the navigation tools within ERDAS VGIS were positive, but further work was required on issues of a more technical nature, including the sensitivity of movement to the direction indicated by the user.

Currently, the use of 3D models could be argued to be contributing added value, and widening the range of materials and media by which communications and engagement can be undertaken. However, based upon the ease of access to raw data, the potential to extract derived data suitable for use within the VR systems currently available, and the low cost of model development compared to the potential costs of changes in land use, it is reasonable to believe that such models could become a core means of engagement in exploring scenarios of change into the future

5. New opportunities: new sources, methods and applications

The purpose of this section is to introduce a selection of ongoing research at the Macaulay Institute into new sources of RS data, new means of change detection using RS data, and an example of a new use of RS data in land resource assessment in the rangelands of north and west Scotland.

5.1. New data sources: synthetic aperture radar (SAR)

Since the 1940s, the development of diverse remote sensing techniques and methodologies in radar imaging and Synthetic Aperture Radar (SAR) has advanced rapidly (Boerner *et al.*, 1998), and novel methods of the processing of radar data are significantly enhancing the value of Synthetic Aperture Radar imaging (Boerner and Cloude, 2002)

With SAR, the textural fine-structure, target-orientation and shape, symmetries and material constituents can be recovered with considerable improvements above that of standard radars or electro-optical imaging systems. The advanced interferometer radar provides the vertical spatial structure (Cloude and Pottier, 1996), whereas the Polarimetric-Interferometric Synthetic Aperture Radar recovers the co-registered textural and spatial properties simultaneously (Cloude and Papathanassiou, 1998). This includes the extraction of Digital Elevation Models (DEMs), with the additional benefit of obtaining co-registered three-dimensional information (Schuler *et al.*, 1996).

Extra-Wide-Band SAR imagery, when applied, can provide differential background validation and measurement, and the capability of monitoring vegetation stress with hitherto unattained accuracy (Stebler, 2002). More recent studies have shown that applying multiple parallel repeat-pass SAR images along stacked (altitudinal) or displaced (horizontal) flight-lines will result in Tomographic SAR Stereo-Imaging, including foliage and ground penetrating capabilities (Reigber and Moreira, 2000). It is shown that the accelerated advancement of these modern SAR imaging techniques is of direct relevance, and paramount priority, to the acquisition of ground-truth data for wide-areas and dynamic environments (Boerner and Yamaguchi, 2000).

Recent developments in polarimetric interferometry and multi-baseline radar tomography (Boerner and Cloude, 2002; Bamler and Hartl, 1998) use longer wavelengths, such as L and P bands. These techniques provide penetration into vegetation and the ground and hence provide vertical structure information not available from optical or laser sensors (Papathanassiou and Cloude, 2001). This technology promises to provide the basis for important new radar remote sensing instruments for global biomass and vegetation mapping (Treuhaft and Siqueria, 2000).

The implementation of such novel application and methods will, however, fail unless fully calibrated data are available to the vast community of environmental scientists. It is now possible to access the data that is acquired daily of remote parts of the globe, from satellites such as the environmental monitoring satellite EnviSAT. However, the opportunities that such data availability can offer should be linked with an understanding of the limits and capabilities offered by the current, and future, global monitoring systems and satellites, such as TERRA-SAR, RADARSAT-2 and ALOS.

The applications of radar remote sensing using Interferometric SAR and Polarimetric SAR analysis form a significant element in the Macaulay's programme of research which aims to add value to mapped land cover classes with attributes such as structure, height and composition. The development of techniques to deliver this aim has been in collaboration with the University of Edinburgh, Forest Research and University of Adelaide, using a study site at Glen Affric, in north-west Scotland. The research formed part of a wider programme of studies into the conservation and management of semi-natural vegetation areas in the United Kingdom.

The radar data collected for the Glen Affric site were airborne, fully Polarimetric Interferometric L band, with baseline of 10 m and wavelength of 0.23 m. The morphological characteristics of the radar backscatter were analysed, with especial focus on the semi-natural areas, Caledonian pine forests, and mixed woodlands. The collective information derived from radar images, land cover height, land cover type, and topography, plus the spectral information derived from optical imagery has been used to produce a new method of classifying areas of known or similar plant communities (Lumsdon *et al.,* submitted).

5.2. Novel data analysis: automated land cover change detection

Automating the process of land cover change detection is a research challenge that has value, not only to the updating of the LCS88 database, but also enabling the development of monitoring systems for wider application. Brogaard and Prieler (1998) monitored land cover change in China between 1975 and 1990 using an automated process for which remotely sensed data provided the basic inputs. Parulekar *et al.* (1994) published a discussion of the computational requirements necessary to provide automated land cover mapping at a resolution of 30 m or less. They argued that the sheer volume of information acquisition demands a high level of automation. In addition, they emphasised the need for flexibility of datasets (multi-spectral, multi-temporal and with multiple resolutions) in order to accommodate the varying requirements of end users. In a similar vein, Berry *et al.* (1995) emphasised the use of multi-disciplinary inputs in the development of any system capable of analysing human-influenced landscapes, while Wen and Tateishi (2001) aimed to produce a land cover dataset for the whole of Asia using the NOAA AVHRR 1km dataset, for which they used climatic and DEM data alongside the spectral reflectance information. Civco *et al.* (2002) carried out a comparison of various land use and land cover change detection techniques, and argued that no single method is capable of providing complete answers.

The conclusion drawn from these research projects is the value of a fusion approach, where different methods are applied to different problems. To support this approach, expert systems may be used, in which knowledge and experience of human experts can be acquired and represented within an automated system. Examples of such an approach have been published by Song and Civco (2002), who used a knowledge-based system to reduce the effects of cloud and cloud-shadow on remotely sensed images, and different approaches to the analysis of land cover and change (Brodley *et al.*, 1996; Smith and Fuller, 2001).

ETORA-II, an Environment for Task-Oriented Analyses, is an environment in which blackboard-based expert systems can be implemented. It is based upon the Gensym G2 software development environment, and comprises a number of task specific software components, such as interfaces for the developer and an interpreter. These interfaces provide functionality for the construction and utilisation of applications and means of representing agent-based knowledge ‘experts’.

A package of software modules, ‘SYMOLAC’ (Skelsey *et al.*, 2004) has been developed to enable an automated approach to updating land cover datasets. It makes use of polygons within a land cover dataset, such as LCS88, by examining each in turn, and then adds attributes and values, including those for slope, soil and other environmental factors, to each polygon. Image analysis techniques are used to provide other measurable characteristics, such as texture, derived from remotely sensed imagery. A combination of expert heuristic knowledge and other supportable evidence is used to assign positive or negative evidence to hypothesised land cover classes.

The current implementation of SYMOLAC contains expert heuristic information for every one of the standard non-mosaic land cover classes in the LCS88 legend. This enables it to reject a large proportion of the possible transitions from one land cover type to another as unlikely or not very likely. In its current state, SYMOLAC is not yet capable of updating all of the classes recorded in the LCS88 dataset. However, the framework that enables this to be done is now in place, and additional methods of textural image analysis have been identified that, when implemented, will allow rapid and accurate identification of land cover classes from remote sensing imagery. Outstanding issues remain how to accommodate new classes that were not recognised, or did not exist, within the LCS88 dataset.

5.3. New Applications: Rapid Habitat Assessment

Sustainable use and management of the extensive upland vegetation resource in Scotland is a key objective for land managers. This often involves finding a balance between traditional agricultural systems, sporting management, conservation and amenity use. In recent years, there has also been a greater realisation of the natural heritage value of the hill and upland rangelands, linked with obligations under EU legislation for the conservation of internationally important habitats, notably dry and wet heathland and blanket bog.

Together with rough grassland and other hill, upland and mountain grazing vegetation types, these rangelands comprise some 15,000 km^2 (18% of the total land area of Scotland) which are grazed by free-roaming wild and domesticated animals. MacDonald *et al*. (1998) described a system for assessing the impact of large herbivores on upland vegetation. This system uses a range of indicators (mainly plant based) to describe the level of impact of grazing herbivores on different types of vegetation communities. A method for applying this system to large areas has been developed at the Macaulay Institute (Stolte *et al*., 2000) using the LCS88 dataset to identify the location and extent of the different vegetation types on the area to be surveyed. Sample areas are then selected at random within the LCS88 polygons, and a field assessment of grazing and trampling impacts is undertaken. Mean impacts are then predicted for areas not sampled, and an overall map of impacts produced.

This methodology has been applied in the survey of a number of the Deer Management Group areas in Scotland, in collaboration with the Deer Commission for Scotland and Scottish Natural Heritage. However, a number of issues have arisen from this initial research, notably that there can be considerable spatial variation on impacts within larger polygons in the LCS88 dataset. Although the LCS88 provides the boundaries and general distribution of vegetation types needed for this work, only site-specific detailed surveys can provide information (often insufficient) about the variability in impacts within a land cover type. There is a need to identify the causes of this variation with a view to enhancing the accuracy and predictability of the model.

Factors such as within-polygon variability in aspect, slope, topography, extent of present-day burning, and fragmentation of vegetation patterns are all likely to affect herbivore distribution and therefore grazing impacts. One strategy is to relate high-resolution vegetation indices derived from remotely-sensed satellite data, to such variables as vegetation cover and biomass and a time series of low-resolution data to examine regional variation (Marcal and Wright, 1997). However, the direct calibration of remotely-sensed vegetation indices is problematic because of a need for time-synchronous sample data of an area equivalent to several satellite pixels. Work at the Macaulay Institute has indicated that, for the major rangeland vegetation cover types, a satisfactory substitute may be found using a calibrated vegetation dynamics model, such as the Macaulay Heather Moorland Management Model (Wright *et al*., 1997).

The fundamental role played by land cover data in enabling the development of materials to support more informed decisions about natural resources indicates the importance of maintaining the currency of such datasets, and for adding value to the existing information. New sources of data for operational use, such as radar and techniques for updating information on land cover, are two research themes which are directed at providing such support.

6. Conclusions

The examples provided by the Soil Survey of Scotland, the Land Cover of Scotland survey and the more recent work on landscape analysis in support of planning for renewable electricity reveal two important trends: i) the changing role of RS data from intermediate sources of information (where they were discarded afterwards) to RS data being both a source and a key part of an integrated database; ii) the degree to which users were involved in developing the applications - from the Soil Survey which was essentially scientist-led, to the mixed model of the LCS88, and towards the current model where the users are directly involved in the specification and development of the information products.

These trends are partly a result of technological developments but they also are due to the changing role of ‘experts’. In the past, as the experience of the Soil Survey of Scotland and other similar surveys show, land resource assessment was very much the domain of the ‘expert’ and was generally science-driven. Increasingly, however, this situation has changed. Now land resource assessment tends to be ‘issue-driven’ and ‘customer-focussed’. This requires a different set of skills of the ‘expert’, communication as well as technical skills. Looking to the future, there is little evidence of these trends changing. Remote sensing technologies will continue to deliver new and potentially useful data sources but the challenge for the remote sensing community will remain that of translating their potential into useful tools. Another lesson from this paper is that, whilst we have been using RS data in resource assessment in Scotland for over 60 years, there is a lack of awareness of this having been the case. It is important that this lack of awareness is addressed because it has probably led to the systematic under-valuing of remote sensing technologies both by potential users but also by the remote sensing ‘community’ itself.

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