Colour infrared aerial photography as a tool for vegetation mapping and change detection in environmental studies of Nordic ecosystems: A review

MARGARETA IHSE

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The aim of the paper is to sum up knowledge of colour infrared (CIR) aerial photography as a tool for vegetation data for mapping and monitoring in environmental and biodiversity surveys and change detection surveillance. It compiles thirty years of research of the main ecosystems in Swedish vegetation, where the overall goal was to develop methods for mapping and monitoring vegetation by use of CIR aerial photographs, assess the accuracy compared to field-based mapping and to implement them as a tool in nature conservation and environmental planning. The methods include development of a classification system, identification and analysis of indicators, development of interpretation techniques, and evaluation compared to the data collected in the field. The CIR observable criteria are colour, texture, pattern, size, form, and density, based on spectral reflectance, physiognomy, life forms, ecological conditions, moisture and nutrition, vegetation period and phenology, topography, site conditions, and management methods. The methods have been used to produce vegetation maps of mountains, boreal forests, and mires in northern and central Sweden, in national inventories of wetlands, ancient meadows and pastures, key biotopes in forests and for monitoring agricultural landscapes.

Keywords: *colour infrared aerial photographs, interpretation methods, monitoring biodiversity, vegetation changes, vegetation mapping*

Margareta Ihse, Department of Physical Geography and Quaternary Geology, Unit for Ecological Geography, Stockholm University, SE-106 91 Stockholm, Sweden. E-mail: margareta.ihse@natgeo.su.se

Introduction

Background

This paper summarizes the experiences of several decades concerning methods and knowledge related to vegetation mapping in CIR aerial photographs, including practical means of how to use visual interpretation. The focus is on methodology, but as important in my opinion, examples are given of how these techniques have been used in different ways in practice for nature conservation and environmental planning, for surveys and monitoring. The methods and results could also be helpful for dealing with classification of high and medium resolution satellite imageries, as they often use and rely on aerial photographs for interpretation of test areas of satellite data, as a base for the automatic classification.

Aerial photographs on colour infrared film still provide one of the best sources of information on ecological conditions in the landscape and on the status of and changes in vegetation. The advantages of aerial photos are clear. They are cheap and easily available. The information is easy to extract without using advanced methods and instruments. They provide raw data which can be classified and reclassified according to different aims. They combine details and overviews ranging from 0.5 to 2 m^2 to 150 km^2 (in the aerial photos normally used in Sweden). As they have been taken at regular intervals, they provide information covering the past 60 years and enable us to monitor long-term patterns of change in vegetation and to study vegetation dynamics. In this way they provide reference data for all parts of the landscape.

They are not outdated or replaced by satellite data, but are complemented by such data. The few tests so far carried out on similar vegetation and habitat show that very high spatial resolution satellites, such as IKONOS, will probably be able to provide data of similar or near similar quality (Allard 2003b). A highly important feature of stereo aerial photos, compared to the single images of a satellite, is that they easily show the landscape in three dimensions. This is of importance not only in evaluating the height and structure of vegetation but is also of great value in providing quick information concerning the topography of landscapes, geomorphologic features and soil distribution, all of which are important features affecting the distribution of vegetation, especially in a glaciated landscape. To obtain the same topographical and height information in three dimensions as can be done from the stereo interpretation of aerial photographs, the satellite imagery must be analysed together with high resolution digital elevation data (Groom et al. 2006). Another important advantage is that aerial photos can be taken at the moment when weather conditions are optimal. Heavy cloud covering areas and objects is a general problem in satellite remote sensed data, especially in the northern temperate zones, since the satellite passages occur at fixed times, although the problem is less acute now because the number of earth observation satellites, and hence the number of passages, have increased.

For manual mapping of vegetation, colour infrared aerial film (CIR) has many advantages over panchromatic black and white aerial photography. CIR film is better for distinguishing between different types of vegetation, since foliage reflects and transmits much better in the near infrared wave length than in the visible part of the spectrum.

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This phenomenon has been thoroughly investigated and has been well-known for a long time (Colwell 1960). CIR film is also more suited for differentiating between different soil moisture contents, between vegetation and soils in different conditions, such as mineral soils, substrate, humid topsoil, bedrock outcrops, or thin soil layers (Lundén 1977), and between living, damaged and dead vegetation. It can also distinguish stressed and damaged vegetation at an early stage, often 'pre-visual', i.e. before it can be detected in the field (Wastenson et al. 1987).

CIR aerial photographs have been used in Sweden for more than 30 years to map and monitor for nature conservation purposes as well as for physical planning of the environment (Ihse 1977; Ihse et al. 1977; Dahlberg 1981). Several methodological studies have been undertaken in most of the Nordic ecosystems: in mountain vegetation, in forest vegetation, in mire vegetation in urban and semi-urban vegetation, and in grassland vegetation in agricultural landscapes, mostly in pastures and meadows (Ihse & Wastenson 1975; Ihse 1978; Rafstedt & Andersson 1982; Löfvenhaft 2002; Löfvenhaft et al. 2002; Ihse & Blom 2000; Ihse & Lindahl 2000).

Although these studies were based on Swedish vegetation types, the methods and indicators used have a common and general approach in any part of the world. Throughout Sweden, Europe, and the whole world – the emergence of new socio-economic conditions and the scale enlargement and introduction of new methods in agriculture and forestry (Antrop 1998; Krönert et al. 1999; Mücher et al. 2000) have led to profound quantitative and qualitative changes in land-use, landscapes and vegetation during the past century, particularly in the last 50 years. Many of these changes are of the same type and proceed in the same direction, albeit at different rates (Ihse 1995; Skånes 1996; Brandt et al. 2002; Bastian et al. 2003). Many of these changes can be documented by the interpretation of chronological series of aerial photographs. Such repeated measurements can be used as bases for monitoring.

There has been and still is a focus on species when undertaking surveys for mapping and monitoring for estimating biodiversity or changes in biodiversity or estimating the ecosystem functions. There are, however, many advantages in choosing to focus on vegetation types, habitats or biotopes, together with the landscape patterns and landscape structure in which it they are embedded, as is done in landscape level studies, instead of on separate organisms. Vegetation is the main ecological feature in landscapes: it is the primary producer, the most obvious biotic component in ecosystems, a good bio-indicator correlating closely with several physical geographical features, and tends to mirror the combined biodiversity of plants and animals. Such vegetation studies are thus giving the potential for certain species diversity, but not necessarily the current species biodiversity. Vegetation changes are evidence of environmental impacts that might be of importance to the functioning of the ecosystem and to biodiversity maintenance, and represent the cumulated effects of the different types of environment. On a higher spatial scale, the pattern–process interactions in which vegetation units play a dominant role, is the subject of landscape ecology.

Today it is difficult to consider broad-scale vegetation studies and landscape ecology without remotely sensed data, which includes satellite imagery as well as aerial photographs (Bastian & Steinhardt 2003; Löffler 2003). Vegetation is the most conspicuous component of the environment, especially in remote sensing images operating in the visual to near-infrared wavelengths. The focus in this paper is on methodologies for vegetation mapping by CIR aerial photos. It will not go into detail of more technical-oriented approaches, as with studies of spectral signatures or reflectance studies, nor will it go into comparison with studies of other remote sensing methods. Some selected references from detailed studies investigating spectral reflectance, as the bi-directional reflectance of specific importance in boreal forests, are Pellika et al. (2000) and Mikkola & Pellika (2002). Nordic studies on a landscape scale, based on satellite remote sensing are found in, for example, Kalliola & Syrjanen (1991), Johansen et al. (1995), Nordberg & Allard (2002).

Aims

The major aim of this paper is to sum up techniques for manual interpretation in CIR aerial photographs, to illustrate how these methods have been used in practical mapping and change detection in different Nordic ecosystems, and to present a compilation of the results obtained from several projects using CIR/aerial photography during nearly 30 years of research on vegetation, ecosystems and biodiversity, with examples from Sweden. The paper has two focuses: factors of importance for the understanding of vegetation mapping by aerial photographs, and changes that have occurred in vegetation and land-use. The aim of this paper is also to document CIR as a mapping technique that can be used in environmental monitoring and thus set examples for potential users. The main goal of the vegetation studies presented here was to investigate the possibility of mapping vegetation from CIR aerial photographs in order to describe vegetation status and changes of significance to biodiversity. Sub-goals were to develop methods, assess and define indicators, and assess the accuracy of data collected by aerial photos versus data collected in field studies. This research was intended to supply methods for mapping and monitoring for the benefit of nature conservation and environmental planning, so that it could be used to assess ecosystem functioning and potential spots of high biodiversity.

Selected ecosystems and study sites – vegetation status and changes

The key selection criterion for Swedish ecosystems for the various research projects was a high degree of naturalness, leading to high biodiversity (or potential biodiversity) expressed in species or in habitats. Other landscapes were selected due to their long management continuity, such as specific meadows and pastures and other small biotopes with grassland vegetation in agricultural landscapes. The ecosystems selected were: mountains, mires, agricultural landscapes with a grassland ecosystem, and forests of nemoral and hemiboreal deciduous types (summarized in Table 1). A short description of the vegetation types in the different ecosystems are given in the following, to better understand the methods selected and the results found. For a more complete description see the separate reports referred to.

The Scandinavian *mountains* are one of the largest wilderness regions in Europe (50,000 km^2. Many parts are difficult to access, and it is thus both difficult and expensive to make field-based vegetation maps. When the Swedish Government and The Swedish Environmental Protection Agency needed basic data for physical planning and nature conservation it was an appropriate choice to start to test CIR aerial photography for vegetation mapping in the mountains, and compare and evaluate the accuracy between black and white aerial photos and field-based inventories. Eight large test areas covering both southern and northern plant communities were selected for basic mapping. They represent the different types of vegetation found in Scandinavian mountains: high alpine vegetation on bare rock, snow beds, middle-alpine grass heath, dwarf-shrub heaths of dry, mesic and wet types, meadows, mires, willow shrub, and birch forests (Sjörs 1956; Ihse & Wastenson 1975; Andersson et al. 1985). Meadows and the nutrition-rich mires in particular are expected to be high biodiversity areas. Another set of 15 smaller test areas was selected to investigate changes in vegetation. These concentrated on recording the differing impacts of tourism and reindeer grazing, to identify changes previously reported by field studies of damage to vegetation cover, disappearing lichen cover, and drained and dry mires (Allard 2003a).

Mires are probably among the last large undisturbed ecosystems remaining in Sweden. They cover large areas in the boreal zone, *c*.20% of the total land area in Sweden, and are distributed all over the country. Many bogs and fens are still in an undisturbed state, i.e. not drained, tilled or afforested. Even though, in most cases, they have low species diversity, the species present are specific to this ecotype. The ecosystem function of mires is highly important for water regulation and nitrogen retention. A large number of study areas, including all representative types of mire, were selected in all parts of Sweden, and a comparison of the interpretation accuracy and possibilities were done in CIR aerial photographs and in black and white photographs (Rafstedt & Andersson 1982). The types of mire were described according to whether they were bogs or fens, (with and without trees), dwarf shrub types, lawn types, soft types, and those rich in ponds or shrubs. The different nutritional types, commonly used in botanical classification, poor, intermediate or rich, could not be used in classifying in CIR aerial films, as they could not be interpreted with any accuracy. The Swedish Environmental Agency's national survey and mapping of wetlands, VMI (Våtmarksinventeringar; National Wetland Inventory), is based on the interpretation of CIR aerial photos according to methodological studies carried out by Rafstedt & Andersson (1982). Raised peat bogs were selected for change detection because they are sensitive indicators of climatic and environmental change. Since peatlands are known to act as carbon dioxide sinks or sources, their vegetation status and changes are important in appraising climatic change. Test areas for studying changes, especially increased growth of trees, were selected in 14 undisturbed raised peat bogs in southern Sweden.

The central and southern Swedish rural landscape consists of *agricultural landscapes*, with long historical continuity, where forests and semi-open landscapes occur mixed with agricultural plains, grasslands, forests, and small, well-defined urban built-up areas (Ihse 1995). Urban sprawl of the type that exists in several places in continental Europe is only found in minor parts. In choosing study areas for basic vegetation mapping, all these landscape types were included, but concentrated on semi-open landscapes, as they display a variation in characteristic vegetation types within a relatively compact area. A total of nine large study areas were chosen in rural districts (Ihse 1978), and two in urban and semi-urban areas (Löfvenhaft & Ihse 1998). In additional, 17 study areas were selected for detecting change. These focused mainly on grasslands and small biotopes (Ihse 1987; Skånes 1996;

Table 1. Study sites used for mapping and change detection in CIR aerial photographs in Sweden.

Ecosystem and vegetation types	Mapping & monitoring	Number of test areas	Approximate size (km^2)	Geographical location
Mountain vegetation	Mapping	8	10–80	Abisko, Sitasjaure, Autajaure, Teusajaure, Ottfjället
	Monitoring	12	4–15	Långfjället, Fulufjället, Sånfjället, Teusajaure, Polluanvare, Rogen-area
Mire vegetation	Mapping	50	0.01–100	Regions of Götaland, Svealand, and Norrland
	Monitoring	14	0.01–10	Counties of Scania, Kronoberg, Jönköping, Östergötland, Skaraborg, and Älvsborg
Agricultural and forest landscape	Mapping	10	10–100	Counties of Scania, Östergötland, Stockholm and Norrbotten
Agricultural landscape	Monitoring	40	10–270	Parishes throughout Sweden (20), Counties of Scania, Halland, Kronoberg, Östergötland, Öland, Sörmland, Västmanland, and Värmland,
Forest, nemoral and hemiboreal deciduous types	Mapping	110	0.01–0.2	Counties of Scania, Kronoberg, and Östergötland
Forest, boreal coniferous		3 areas and 400 plots	150–2500	Counties of Dalarna; Grangärde, Norberg, and Rättvik

Cousins & Ihse 1998). The vegetation consists of six main natural types or land-use types: forest, semi-open land with bushes and trees, open land, wetland, water, and urban/built-up areas. The forests were coniferous forests (pine and spruce), deciduous hardwood forests (oak, beech or ash, and mixed species), deciduous softwood forests (birch or aspen), wet forests, semi-open vegetation types, wooded ancient pastures (*hagmarker* of dry or mesic grasslands dominated by oak or birch), open land of heaths (mainly heather), open meadows (dry, mesic or moist, acid or calciferous rich grass and herb dominated), bedrock outcrop vegetation, arable, wetlands of bogs or fens, urban or built-up areas of varying density and with varying amount of vegetation, forests and deciduous trees of different ages, grasslands and open areas with varying intensity in management, and wetlands. The concept of '*hagmarker*', a Nordic type of wooded meadows and pastures, is such a prominent feature and so important to biodiversity that they were described as separate units. They consist of open land with trees and bushes of varying density.

For monitoring purposes the survey included also classification of management intensity in grasslands and arable fields and the landscape ecological infrastructure of small biotopes. The grasslands are classified into fertilized 'cultural grasslands' and unfertilized 'natural grasslands'. The unfertilized semi-natural grasslands were specifically studied. They embrace both ancient meadows and pastures, with a very long history of continuous use. The natural grasslands are regarded to have the highest biodiversity values in the Swedish agricultural landscape. Their value today, however, depends on the management intensity. Management is listed under three categories: intense and well managed, low and less well managed, and not managed. Well managed means that all of the area is grazed or mowed; low or less well managed means that there are areas of dead vegetation or thick litter not removed as well as areas left without grazing/mowing but with young trees and shrubs; and not managed means that most of the area is covered with bushes, shrubs and young trees, leaving only small areas in the glades of former grassland. Small biotopes were specified as linear objects, such as road verges, stone walls, tree rows, water courses and ditches, and point objects, such as habitat islands in fields, mounds of stones and ponds (Ihse 1996), in such a way that they could be entered into landscape ecological models, e.g. connectivity and dispersal models. They have also been used to understand and estimate the gene diversity in a fragmented landscape (Prentice et al. 2006).

Nemoral and hemiboreal deciduous *forest* biotopes of high natural value and long continuity were investigated in more than 100 test areas in the southern part of Sweden. They have a great diversity of mosses and lichens but only 10 species of deciduous trees. The latter can be placed in three groups: dry to mesic hardwoods, dry to mesic softwood types, and wet softwood types. The dominating species are birch, aspen, oak, and beech. The boreal forest biotopes, which consist mainly of pine and spruce, were investigated at three study sites in central Sweden, in more than 400 test plots. A high diversity of mosses and lichens was found in all these forests, as well as old-growth forests structures, such as wide-crown trees, dead wood, several generations of trees, and irregular glades. Only the status of vegetation in the plots was studied, not its change (Ihse & Kindström in press).

Materials and methods

Films and instruments

The CIR aerial film has very good spectral resolution in the near infrared part of the spectrum, compared to conventional colour film or black and white film, which gives excellent opportunities to distinguish between different vegetation types. Vegetation types and species differ much more in this part of the spectrum than in the visual part. They have also good ability to penetrate haze, enabling photographing from higher altitude with good image quality.

CIR aerial photographs have been produced since the beginning of the 1970s in different selected areas and at varying scales, in black and white since end of the 1930s. The entire country was systematically photographed by the Swedish Land Survey after 1980 on at least one occasion, using CIR aerial photographs (on a scale of 1:30,000 for southern Sweden and 1:60,000 for northern Sweden). In many areas repeated photographs were taken at intervals of 4–15 years, thus allowing change detection as a base for monitoring. All photos are registered in a central archive. The photographs were taken with a camera with a focal length of 152 mm. They were taken with 60% overlap for stereo interpretation. Their spatial resolution is between 1 m^2 and 4 m^2 (1:30,000 and 1:60,000 respectively). The Land Survey produced transparent copies from positive film, instead from negative film. This method allows a better calibration of the colour, intensity and hue in photos taken in different periods and with different films, so that the photos needed for change detection can be compared. Transparencies are used to avoid the dark shadows often seen in paper prints, and to obtain sharper images.

Since 2005 the photographs have been taken with a digital camera, allowing both black and white, normal colour and infrared colour photos to be produced at the same time. At present there is an ongoing intensive development in handling the new digital data with regard to processing, delivery to users and archive. The interval between photographs will be considerably shortened, and there are plans to coverer one-third of Sweden each year.

Different negative scales have been tested and compared – 1:10,000, 1:20,000, 1:30,000, 1:50,000, 1:60,000, and 1:150,000 – with the focus on the medium and small scales, i.e. 1:30,000 and 1:60,000. In some areas photos have been taken during different vegetation periods from late spring to early autumn to study the influence of phenology. The photos were mainly taken during early to high summer, at an optimal time for analysing the vegetation conditions (Ihse 1978; Rafstedt & Andersson, 1982).

For visual interpretation, advanced zoom stereoscopes were used (Zeiss Jena Interpretoscope and Wild Aviopret), with continuous magnification of 2–15 times. Wild B8, a precision analogue stereo instrument has been used for rectification and AP 190 for digitalization and rectification. For fieldwork, a small pocket mirror stereoscope (Wild TSP) was used, together with a specially designed transparent plate, on which the photos were mounted for stereoscopic viewing. For good interpretation, a continuous zoom and large magnification are necessary, thus allowing swift changes between overview and detail. The changeover to total digital handling also in interpretation is currently ongoing, and tests are being undertaken. The system is very promising, but not yet fully operational.

Prerequisites for the detection of vegetation status and changes

A conceptual model describes the prerequisites used to map vegetation and landscape changes by aerial photography (Fig. 1). None of these can be excluded if good results are to be obtained when developing methods for mapping and monitoring.

The first prerequisite is to recognize the inherent possibilities and limitations of aerial photos. It is crucial to consider the geometric characteristics, the type of film, the scale, the degree of generalization needed, the time of day, and the time of year (vegetation period) for photographing the landscape. In this respect, several statements can be made. The classification system used for mapping and monitoring must be adapted to the aerial photos, the film type and the scale, as well as to the purpose of the mapping, i.e. status description or change analysis. Vegetation types and units must be seen as homogenous parts of the photo by spectral, textural and topographical criteria or by complex criteria. Significant vegetation changes or differences must correspond to significant differences in the image interpretation criteria, consisting of spectral differences and additional criteria. The time interval covered by two consecutive photos must be long enough to allow for change to be detectable. For change detection studies, the differences in phenology during the vegetation period must be distinguishable from other changes. Finally, ground truth or other reference information must be available to assess the accuracy of the classification.

The second prerequisite concerns ecological and geographical knowledge. Good knowledge is needed of the correlations between vegetation and physical geographical features (such as bedrock and soils), between geographical location, altitude and climate, between topography, geomorphologic elements and soil distribution, and between soil moisture, groundwater and different nutrition types and bedrock. Good insight into the relationship between habitats and their species is also needed. A good knowledge of the geographical distribution of habitats, as well as their regional and local characteristics, facilitates the interpretation. This is specific for each region or country.

The third prerequisite is knowledge of past and present land-use and management. Knowledge of present land-use should include not only the methods of management but also the intensity of usage and the calendar of management activities. Historic land-use and land organization can be traced from the detailed maps of Sweden that cover almost 300 years, providing information about continuity in management and habitat. This is especially important to the understanding of biodiversity in grasslands and old-growth forests. This is also specific for each region, a part of the cultural history, even if many features are common to large regions.

For the detection of change, and thus monitoring, a fourth prerequisite can be formulated: this concerns both the geometrical and spectral prosperities of aerial photos and ecological knowledge. The minimum area of a changed object needs to be larger than the minimum resolution or mapping unit. The total difference of interpretation indicators resulting from the change (the sum of spectral, textural, height, coverage, location, and form indicators) is as large as or larger than the difference between the classes. There is usually a spectral and textural variation within every class, and if the classes are not distinguished sufficient detail according to expected changes, actual changes could be detected, but would not be differently classified. The observed change must be realistic in ecological terms, and the classification system by which the data are collected must include ‘early indicators’. Knowledge of phenology

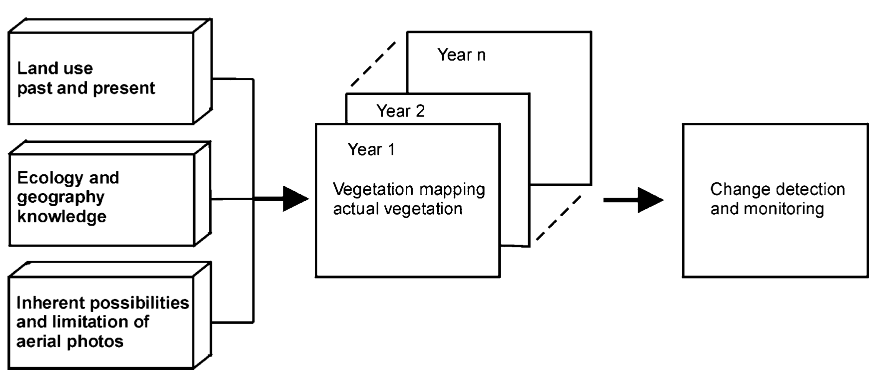

Fig. 1. Conceptual model of the prerequisites to map vegetation and detect changes in aerial photographs.

and natural variation is necessary in order to weed out the cause of the change and distinguish between natural variations and phenology on the one hand and environmental changes on the other. From the knowledge of vegetation successions and from assessments of quality of interpretation, it can be seen that for detection of changes in a monitoring programme the mapping from CIR aerial photos on a scale of 1:30,000 can be repeated for the first time after five to seven years. This is the time needed for the differences from overgrowing of bushes or tree plantations – the most common land-use changes – to be clearly detected.

Development of vegetation classification systems for data collection by air photo interpretation

Any classification system must be adaptable to the aim, the scale, and the nature of the collected data, according to the first prerequisite. This means that there is no general classification system for all types, all scales and all purposes. The system must fulfil the prerequisites for data collected from CIR aerial photographs, and it must be able to identify, describe and evaluate criteria that can be used to distinguish between the various classes. Types of vegetation, habitats and landscape elements are well suited for use as classification units, while units based on individual species are usually less suitable, since only a few species with a very high cover that dominate larger areas can be identified on the scale used in these studies. Classification systems based on the Uppsala school approach of series/vegetation types (Sjörs 1956), or on physiognomy or ecology, are well suited for use in vegetation mapping based on CIR aerial photo interpretation. The system used and developed in Swedish studies is based on a combination of vegetation types, ecological conditions of soil moisture and nutrition, and physiognomy (Ihse & Wastenson 1975; Ihse 1978). The anthropogenic influence, the type of management and its intensity, and the continuity of a particular land-use are also included.

Separate classification systems were developed to cover different ecosystems. However, a basic hierarchical classification system has been developed for general vegetation mapping, for environmental physical planning and for nature conservation, using data provided by CIR aerial photographs on a scale of 1:30,000 (Ihse 1978; Arnberg & Ihse 1996; Löfvenhaft & Ihse 1998). It consists of more than 50 classes arranged in a hierarchical system. The film scale, 1:30,000, allows both detailed mapping with the production of maps on a scale of 1:10,000–20,000 and overview mapping allowing the production of maps on a scale of 1:50,000, the two scales most commonly used for Swedish planning maps (Ihse et al. 1993).

The basic classification system has been adapted and modified for specific purposes. Several studies have been devoted to understanding the effects of vegetation and biotope changes on fauna and flora. For bird habitats, the number of classes of deciduous forests were increased (Robertson et al. 1990), for grassland habitats and for ancient meadows and pastures, classes were added describing management intensity and management types, included land-use classes with a long continuity (Bengtsson-Lindsjö et al. 1991; Ihse & Lindahl 2000; Norderhaug et al. 2000), for landscape structure, the classes for trees and bushes were extended (Cousins & Ihse 1998), and for the subalpine grasslands and meadows, classes describing disturbances and historic management were added (Sickel et al. 2004).

When monitoring agricultural landscapes the focus is on grasslands and types of meadows as well as on deciduous trees, the type and intensity of management, the density of trees and bushes, and the ecological infrastructure of the landscape, including small biotopes, the size and forms of agricultural fields, and the total area of open land versus forested land (Ihse 1996). In particular, unfertilized semi-natural grasslands, consisting of ancient meadows and pastures of long continuity, were studied in detail, as mentioned. The Swedish Landscape Inventory and Monitoring (LiM) programme on agricultural landscapes is based on this method (Ihse & Blom 2000), and it is a prominent part of the NILS programme, the National Inventories of Landscape in Sweden.

Methods for defining interpretation criteria

The interpretation criteria, here called indicators, are an essential part of the model. To describe and distinguish colour as an indicator, it is important for comparative purposes to have a reference. For this purpose, two different colour reference atlases were tested: the Swedish Hesselgrens colour atlas, whose description of colour, hue and intensity according to codes enables a large number of colours to be described, and the American ISCC colour chips from the Munsell colour scale, which has readily associated names but fewer colours (Ihse & Wastenson 1975).

Colour is one of the most important indicators, but it does not give enough information to be used alone in classification, and several other indicators need to be used. The directly observable indicators are colour, texture, pattern, size, form, and density. Most of the indicators have three to five variables each.

Directly derived from the photos are:

- Spectral reflectance (chroma, brightness value and hue)
- Physiognomy (texture, patterns, life forms, vegetation density, vegetation height.

Derived from complementary ecological knowledge are:

- Ecological conditions (soil moisture, nutrition status)
- Site (geographical position, ecological position, topographical position, exposition)
- Species (only dominating and with high vegetation cover)
- Substrate (bedrock, soil type, element of geomorphologic form)
- Anthropogenic influences (fences and hedges, buildings, roads, ditches) and management (ploughing, tree plantation, grazing, mowing).

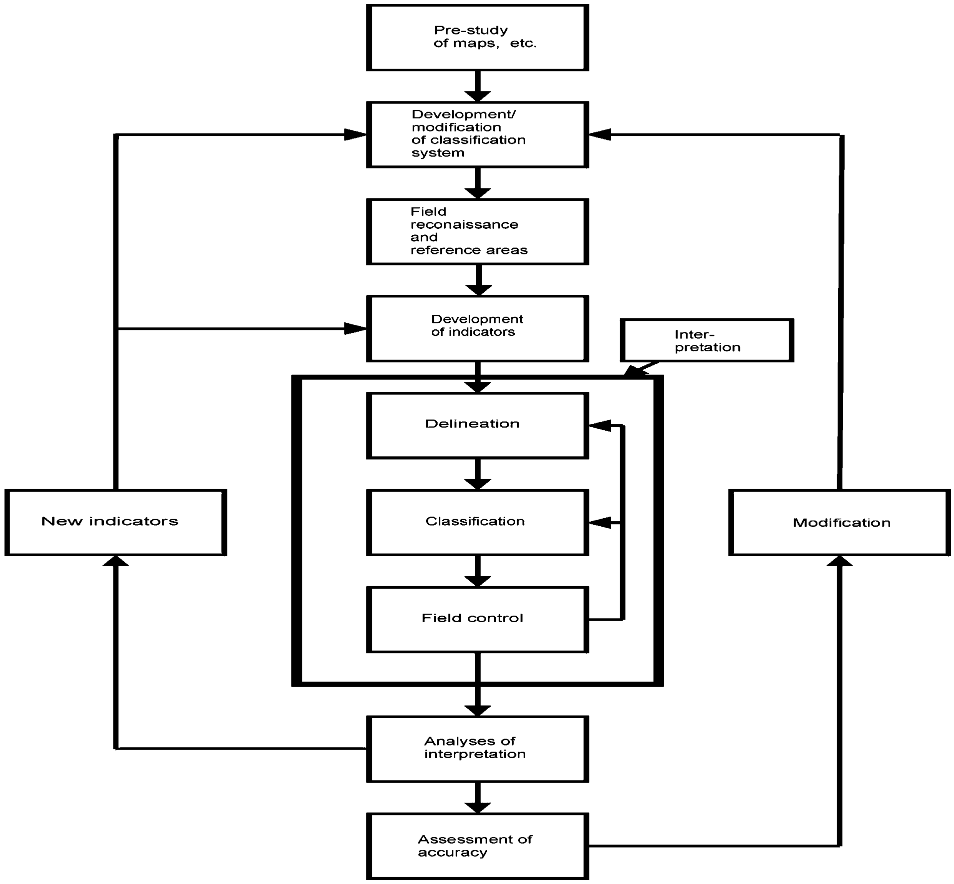

Fig. 2. Model for interpretation and indicator development in CIR aerial photos with a feedback system.

Methods for mapping the present-day vegetation

The model used for interpretation combines methods for discovering, delineating, and classifying homogenous units (Fig. 2). The methodological approach is a feedback system, which includes the development of a classification system, the identification and analysis of indicators, the development of interpretation techniques and the evaluation of accuracy and efficiency, the comparison of data collected by aerial photos against data collected in the field, and the time taken. If accuracy is poor, or the time needed in the field is too great, the classification system is modified and the indicators have to be redefined or further developed.

The following steps are used:

A. Preparation with pre-studies of geological, topographical and cadastral maps, descriptions, and literature (1), development of a classification system (2), field reconnaissance and the selection of reference areas (3), and the selection and description of indicators to interpret CIR aerial film (4).
B. Interpretation consists of delineation (5), and classification (6).
C. Field control (7).
D. Analysis and evaluation consists of analyses of the interpretation (8), and the assessment of the accuracy of the interpretation, (9). If the accuracy is good, the classification system and the indicators are fixed. If the accuracy is poor, there must be a feedback loop, repeating steps 4–9, until the quality of the evaluation is acceptable. This feedback loop must sometimes also go back to step 2, allowing a modification of the classification system.

Aerial photos contain much information: there is estimated to be more than 52 million elements in a 23×23 cm photo on a scale of 1:30,000. This is calculated from the photographic resolution (measured in lines per mm) of smallest detail recognizable of 0.03 mm, at a contrast of 1:1.6, a normal contrast on landscapes (Wastenson 1993). It is difficult to detect and combine everything at one and the same time. The method includes a systematic repeated search, beginning with the easiest features and proceeding to the most difficult ones. The photographs are systematically searched several times in parallel sections, from left to right and from top to bottom, each time concentrating on only one class, or one element. This enables the interpreter to use the same references the whole time, which is important, since small difference or combined indicators are often used (Fig. 3).

The delineation starts with the elements that are easiest to distinguish, delineating forests from open land. Next, agricultural fields are delineated from grasslands; in the

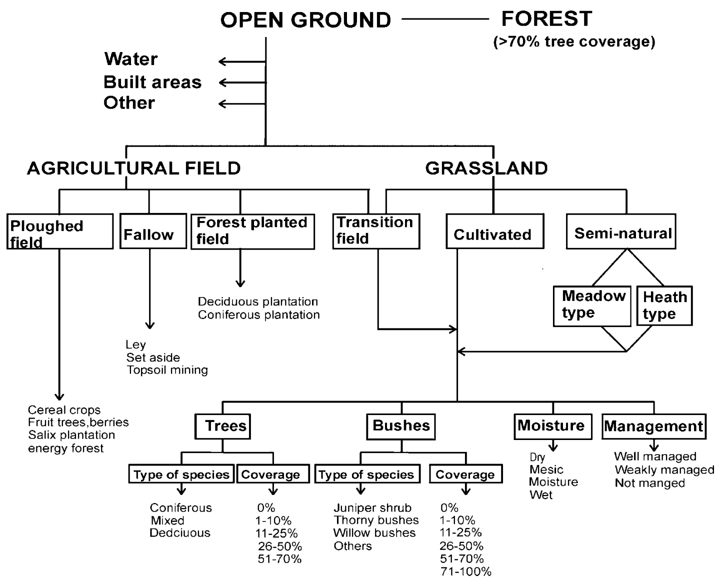

Fig. 3. Decision tree for monitoring of vegetation and habitats in agricultural landscapes.

grasslands, semi-natural grasslands are distinguished from cultivated ones; in semi-natural grasslands, meadows are distinguished from heath types. Semi-natural meadow grasslands are delineated and classified according to the soil moisture regimes, and in wooded meadows, also according to the species and coverage of trees and the types and coverage of bush species. Finally, management types and intensity are delineated and classified. The same procedure is repeated for forests, wetlands and built-up areas, using the appropriate classes.

These methods of mapping include detection, delineation and classification directly on the CIR aerial photos. The polygons are drawn on a transparent overlay with thin ink pens, or are digitized directly in an analytic stereo-plotter. The photos can also be used to survey selected habitats by searching for all possible habitats of one type that meet certain criteria. In the national Swedish survey of ancient meadows and pastures, all grasslands were surveyed in the first step, after which those with indicators of fertilization or other interference to their semi-natural status were sorted out (approximately 80% in most areas in Sweden). The remaining 20%, potentially high-value meadows, were all visited in the field to look for species to be used as field indicators.

Methods for detecting change and for monitoring

Three different approaches have been developed, depending on the aim and the object of monitoring:

(1) total repeated mapping
(2) change control mapping
(3) comparative mapping in ‘false’ stereo-pairs.

In total repeated mapping, all boundaries are drawn and the polygons classified the first time they are monitored, T_1, and they are then redrawn after each subsequent monitoring $T_2 - T_n$. Classification is followed by an overlay analysis in a GIS-system. This is the method normally used when classifying remote-sensed satellite data but it is ineffective and has several drawbacks for visual interpretation. It takes a long time. Generalization and polygon delineation may be carried out in slightly different ways at various times, T_1 to T_n, which may create problems and errors when the overlay analysis of $T_2 - T_n$ is done. In this method, all the areas have to be transformed into geo-referred aerial photos or maps, as they do in the following method.

Change control mapping is the method generally used for monitoring, as it is time efficient and minimizes the errors inherent in overlay analysis (Ihse & Blom 2000). A total mapping of the area, the base-line inventory, is only made at T_1, the first time. This base-line inventory is used as a transparent overlay on the aerial photos in subsequent monitoring, T_2 – T_n. The monitoring is thus determined by the base-line polygons from T_1. Each delineated polygon from T_1 is checked at T_2, regarding boundaries and classes. All changes are checked against the T_1 protocol. Only the changes will be recorded. Changes can thus be defined as added or deleted polygons, or as reclassifications inside the old boundary, together with the T_1 layer, in a GIS-system, for instance ArcView. In the LiM monitoring project of Swedish agricultural landscapes, in the first total mapping, T_1, (the base-line mapping), the number of delineated and classified polygons may vary between *c*.200 and *c*.500 or more in one stereo-pair (at scale 1:30,000), depending on the character of the landscape. Most of these polygons remain unchanged during a monitoring period of five years. Between the second and third monitoring, T_2 – T_3, in this case 1996 and 2001, changes in content or shape were recorded in only approximately 5 to 15 of these classified polygons (between 2% and 7%).

The ‘false stereo-pair’ method is a quick method of detecting minor changes in small objects that are well differentiated from their surroundings by high contrast in the aerial photos. It is suitable for small changes that are difficult to delineate accurately. Change detection is performed in a false stereo-pair, consisting of one photo from T_1 and another from T_2. This method has been used to detect the expansion of wind heaths in mountain vegetation, or the occurrence of new mineral soil as spots signalizing erosion (Allard et al. 1998). The object defined is delineated or marked with symbols on a transparency. Areas with differences in appearance show up clearly. The changes may be detected by blinking, looking at a stereo-pair first with one eye and quickly changing to the other. The comparison can be made very accurately. The spectral definition of black and white photos is too low for them to be used as a single data source in detailed vegetation studies, but the false stereo method allows the comparison of old black and white with the CIR photos. This means that the information content of the 60-year span of black and white photos can be recuperated in the false-stereo comparison with the 30-year span of CIR photos.

Field control and assessment of accuracy

To evaluate the accuracy of vegetation mapping based on CIR aerial photographs, an assessment is made of the degree of detail provided and how well the vegetation boundaries and the classification are in accordance with field estimated data (for full details see Ihse & Wastenson 1975 and Ihse 1978).

The assessments are primarily made by comparing interpretation with field classification. A few comparisons have also been made between different methods of data collection, as well as between remote-sensed satellite data from medium-resolution Landsat TM and high-resolution IKONOS and CIR aerial photographs (Boresjö-Bronge & Rud 1995; Allard 2003a).

Field classification can be carried out by visiting all areas delineated and classified in aerial photos, or by visiting either randomly sampled or strategically selected polygons or sampling along transects. Transects are often the most efficient. The transects are laid out as bands *c.*30 m in width, because it is usually difficult to precisely identify smaller lines from the photos in the field. Transects must start and end with quite easily identifiable features, both on the ground and in the photos. They should not be too long, since the geometry from the central projection of the aerial photos should not influence the compass lines in the field. Transects can be arranged as a triangle, thus starting and ending at the same point. GPS facilitates recognition, but it is not feasible to use it in all forested and mountainous terrain. During fieldwork the indicators and parameters used are checked, as well as the total classification of types and habitats. Accuracy is assessed using a matrix table. The results of the analysis of accuracy are used – if necessary – to reorganize the classification system in a feedback loop.

Results

The results will be given as a qualitative description of general indicators, and their scale and time dependence. A more quantitative description is given of the changes found in vegetation and landscape and for the overall interpretation accuracy in classification.

Analyses of general indicators

The indicators, the interpretation criteria, can be divided into two classes: those used for open land, such as agricultural landscapes, mountain landscapes, or mires, and those used for deciduous and coniferous forests (Table 2).

Colour is the most important criterion, but it should always be used in combination with other indicators, as none of the types of vegetation or landscape elements (or only a very few), can be interpreted using only a single indicator. Different vegetation types with about the same spectral reflectance may be seen as the same colour. A simplified and summarized description of the colour of mountain vegetation in CIR aerial photographs is given (Fig. 4). The colours are described as belonging either to the blue or to the red scale, distinct from each other. However, in practice, there are no distinct limits between the different colours. A few groups of more or less the same colour can be distinguished. The vegetation types with no or little cover are found in the blue part, and those with a high cover and high biomass, in the red. Snowfield beds in the valleys on lee sides and heaths exposed to the wind on hilltops have about the same bright blue colour. Even if there are greater differences in colour than shown here in this summary, the differences are too small and too varied to be used alone as accurate indicators.

Texture, *vegetation height* and *density of vegetation cover* have to be used together with colour. The combination is different for nearly every unit in the classification systems used. The indicators used are not ranked in order of importance. Three-dimensional viewing is necessary when using the following indicators: vegetation zonation,

Table 2. Interpretation criteria used for vegetation and landscape elements in CIR aerial photographs.

Indicators in open land		Indicators in forest	
Directly interpreted	Indirectly interpreted	Tree and bush species	Field layer – forest type
Colour	Vegetation cover	Colour	Sites/ecological position
Texture	Vegetation density	Crown size/width	Crown cover (density, shape, texture)
Vegetation height	Soil moisture	Crown pattern and density	Vegetation height
Topographical position	Ecological position	Crown profile	Heterogeneity in crown cover
Size	Geographical position	Crown cover texture	Soil type
Shape	Site/landscape position	Sites	Soil moisture
	Management/influence	Shadow pattern	Groundwater level
		Phenology	Dead wood (laying, standing)

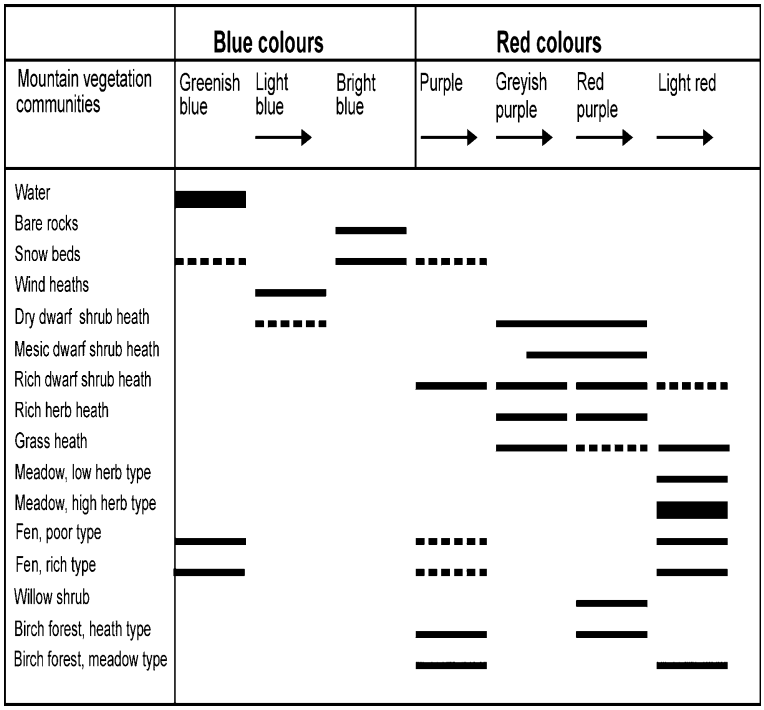

Fig. 4. Schematic sketch showing colour as a distinguishing and overlapping indicator in CIR aerial photographs for mountain vegetation.

topographical and ecological position. These indicators for the mountain vegetation are summarized in Table 3.

It is fairly easy to demonstrate the connections between the indicators and the classes of vegetation in the mountain vegetation of Sweden. The mountain ecosystem is, in a sense, simple, with a small number of vegetation types and species: only one or two layers of vegetation (bottom and field layer) in the alpine zone and, in the low-alpine zone, only a few sparsely growing species of trees or bushes. In addition, there is high correlation between abiotic and biotic parameters, such as snow cover and soil type, as well as low anthropogenic influence. Agricultural landscapes or managed forests are much more complex. There is a greater number of species, several vegetation layers may cover each other and there is much greater anthropogenic influence, often breaking or blurring the correlations between abiotic and biotic conditions.

Scale dependence and combined indicator analysis

The combination and use of indicators is scale dependent. This also depends on what degree of magnification the stereo instruments are using. A test for interpreting areas of high nature value and those with a high potential biodiversity in nemoral and hemi-nemoral deciduous forests was carried out; in the test, the normally used simple stereo instrument (Sterant) with a magnification of 4 times was compared with an advanced instrument with zoom and a magnification of 10–15 times (Aviopret). Six of the nine criteria tested could be interpreted with about the same accuracy by both instruments (50–95%), but for the three most important criteria there were clear differences. Using the low magnification instrument it was very difficult to interpret dead trees and old-growth trees. The accuracy varied from the low magnification instrument to the high magnification by 25–65% for dead lying trees, by 55–95% for dead standing trees, and by 90–98% for old-growth trees (Ihse 1993).

A scale of 1:30,000 allows the indicators: texture, structure, the form of trees, and topographical position to be used to distinguish small but important vegetation differences in agricultural landscapes. It gives good accuracy in drawing boundaries; it allows the classification of many different types of vegetation, habitats, moisture types, field layers, structures, management methods, and small changes. On a scale of 1:60,000 these indicators cannot be defined, and consequently, units that are dependent on these indicators in the classification scheme cannot be used. The same is true of indicators dependent on an exact definition of the topographical position. This means that small landforms or small differences in altitude, which often are of importance to the distribution of vegetation types, cannot be used. High magnification and the ability to zoom are necessary for good identification.

One example of this is taken from the semi-open, mixed agriculture–forested landscape in northern Scania (Fig. 5). The figure shows clearly how the scale of 1:30,000 provides both overview and detail and makes it possible to locate old semi-natural grasslands of potentially high nature value. The image at the top gives an overview of the landscape as well as the situation and distribution of grasslands and agricultural fields, which are bright red in the dark forest-dominated landscape. Close to one of the lakes, in a favourable microclimatic situation is a farmstead, with open grasslands

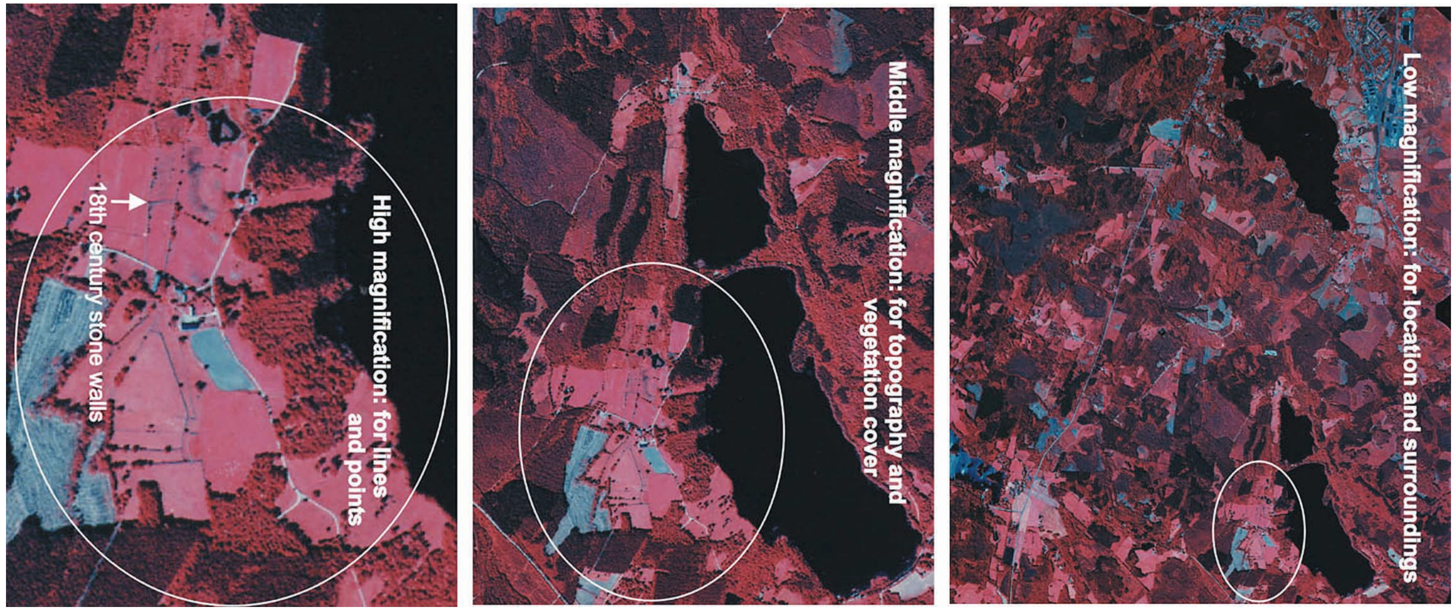

Fig. 5. Different indicators used at different magnifications to identify grasslands of high biodiversity value. Example from Lärkesholm, Scania, showing the importance of a combination of overview and detail (Courtesy of the National Land Survey of Sweden).

and fields surrounding the buildings. The smooth landform is seen in stereo and this shows that the soils consist of fine sediments. Colour, topographic and ecological position, as well as vegetation heights, are used here as indicators. Taken together with the knowledge of historical land-use, it is

Table 3. List of interpretation criteria to distinguish different mountain vegetation types in CIR aerial photos.

	Texture				Vegetation height				Vegetation density				Soil moisture			Vegetation zone/altitude				Topographic position				Ecological position				Bedrock	
Mountain Vegetaion	Very smooth	Smooth	Rough	Very rough	Herbs	Darf shrubs	Bushes	Trees	Scattered	Sparse	Dense	Very dense	Very wet to open water	moist	Dry	Sub – alpine	Low alpine	Middle alpine	High alpine	Hillock	Crest	Scope	Depression	Lesside	Exposed	Bared rock	Snow beds	Calciferous	No. of observations
Bare rock			X	X																									12
Snowbeds	X	X	X		X				X	X			X	X			X	X				X	X	X	X	X			49
Wind heaths			X	X	X				X	X				X			X	X		X	X				X				14
Very dry shrub heath			X						X	X							X	X		X	X								15
Dry shrub heath		X	X			X				X	X	X		X		X	X	X		X		X							33
Mesic shrub heath		X	X			X				X	X	X		X		X	X			X			X	X					14
Rich shrub heath		X	X		X	X					X	X		X	X		X	X		X		X						X	13
Rich herb heath			X			X					X				X		X	X				X						X	3
Grass heath	X	X			X	X					X	X		X	X		X	X				X	X						10
Meadow, low herb	X	X			X							X		X	X		X	X				X	X	X					15
Meadow, high herb	X				X							X		X			X					X	X	X				X	4
Fen poor type	X				X					X	X	X	X	X		X	X	X				X	X				X		11
Fen, rich type	X	X								X	X	X	X	X		X	X	X				X	X				X	X	13
Willow shrub			X			X	X				X	X		X		X	X					X	X						7
Birch fores, heath				X				X		X	X				X	X						X							2
Birch forest, meadow				X				X		X	X			X		X						X							6

evident that these locations have provided good conditions for early settlement in medieval times or even earlier.

In the middle image on Fig. 5 it is possible to identify areas and classify them as grasslands, agricultural fields and several types of deciduous forests. The indicators used are colours, textures, vegetation height and vegetation cover, as well as topographical position.

In the lower image on Fig. 5 it is possible to detect different types of management, as well as the management intensity of the grasslands. Enlargements of up to 10–15 times are used to identify and classify small structures, such as the form and shape of stone walls and stone strings. The indicators used are based on ecological and historical knowledge. The colour of the semi-natural ancient meadows is more or less the same as that of the cultivated modern ones, but the textures are coarser and there are no striped patterns from ploughing. Instead, they have an uneven texture that is the result of grazing and they often have thorny bushes growing on them. The terrain is undulating, with small differences in altitude and soil types, giving rise to a mixture of dry, mesic and moist meadow types in close proximity to each other. They include small biotopes and landscape elements such as stone walls, seen as blue lines, stone cairns and small ancient terraced agricultural fields (seen in stereo). The various forms of the stone walls, short and curved or straight and long, indicate that they were built at different times, from the Iron Age to the 19th century. Taken together, such indicators disclose that the area has been in use for a long time. Thus, the grasslands, still well managed, have probably been managed as meadows or pastures for many hundreds of years. Long continuity often means a high potential biodiversity. Field investigations also supported this interpretation. The land-use today continues an old traditional type of management. For example, in intensely managed landscapes the wet meadow in particular would have been drained.

This specific example from the cultural landscape of south Sweden is given in detail, to better understand this approach to interpretation. It combines indicators from four parameters: the present vegetation, the physical conditions of climate and soil, the present land-use, and the likely historical land use. This approach to interpreting vegetation and landscape elements is general and can be applied, not only to many other areas in the Nordic countries but also to different types of cultural landscapes in other countries.

Time-dependent indicators and analyses of changes

The time of year and the phenology (the appearance of the seasonal development of the vegetation period) are of crucial importance. This is especially true when working with aerial photographs, especially in temperate areas. In the Nordic countries the vegetation period starts at the beginning of May and ends in mid-October. There is more than a month's difference in season duration between southern and northern Sweden, as the distance in between is *c.*2000 km in latitude. The optimal times for southern and central Sweden for some commonly used applications are summarized (Fig. 6).

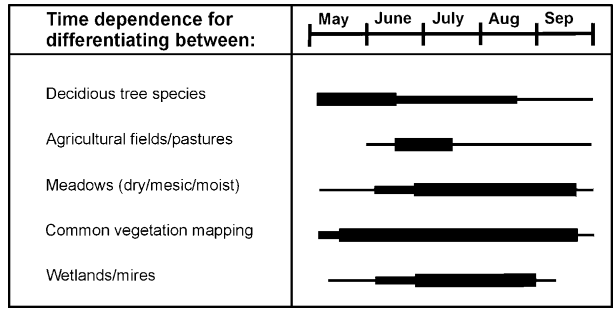

Fig. 6. Summary of varying possibilities for interpreting different vegetation types in Sweden. Thick line – optimal period with high accuracy, medium line – good period with acceptable accuracy, thin line – infeasible period or low accuracy.

Fig. 6 shows that there is no general optimal time for the description of vegetation status for all applications. It varies according to the object or type of vegetation, the topographical site and the geographical position, all of which can lead to differing degrees of accuracy in the interpretation. Changes due to phenology can be used to distinguish better between certain types of vegetation, as is the case for deciduous trees. However, phenology can also lead to misunderstandings and indicate false changes if the comparison or monitoring is executed with photos from different phenological periods.

General vegetation mapping, including all ecosystems and vegetation types, can be performed from mid-/end May until the beginning of September. During this period some types can be more easily distinguished than others. The optimal period for deciduous trees is from mid-May to the mid-June. This is due to large phenological differences during the leafing period (explained further in the following). The agricultural crop fields are best differentiated from grazed or mown grasslands at the end of June, due to the large differences in management practice, with modern hay mowing taking place around midsummer. This gives the newly mown grasslands a bluish colour (showing the mineral soils), while the grazed areas are bright red, and the colour of new crops is a mixture of blue and red, depending on the type. The different types of meadow, dry, mesic and moist, can be differentiated as early as the beginning of June, but the optimal period is in July. At that time, well-managed dry meadows are bluish, due to the dry and dead vegetation, mesic meadows are bright red, and wet meadows have a greenish hue, due to the water content. The accuracy and number of indicators is optimal during a long period, lasting from the end of June until the beginning of September, mainly because there are many different colours that reflect the variation in the amount of biomass production. Mires and wetlands are easiest to identify from the end of June until the end of August. This is due to the late start of growth in wet vegetation types, because water and wet soils are warmed up more slowly than dry soil.

The colour of deciduous tree species varies, as is the case with many other objects, depending on the type of film and the location in the image in regard to the centre position, but especially on the phase in the vegetation cycle when the photographs were taken. Colour is the most important indicator, in particular in interpreting images from late spring to early summer, when the difference in phenology between different deciduous trees is large and when the colour thus is much easier to interpret than texture. Different species of tree come into leaf and blossom at different times, which causes large variations in spectral reflection, and thus differences in colour in CIR aerial photos. The differences and variation in colour are greatest just before the last deciduous trees have come into leaf, as found in early spectral studies by Bäckström & Welander (1953). The common deciduous trees of the Nordic countries come into leaf in approximately the following order: birch and beech, aspen, alder and other softwood species, oak and other hardwood species, and finally ash.

The schematic colour diagram shows clearly how the relationships between species change at different periods, from early summer to late summer (Fig. 7). The colours in the images from early summer (upper diagram) vary between blue and bluish-red to bright red. Buds, stems and branches result in a blue or bluish hue, new foliage in a light red and old leaves in a bright or dark red colour. Trees with incompletely grown leaves are thus seen as very light red with a bluish hue. Taking ash and birch at the beginning of June as an example, the whole ash, with barely sprouted leaves, shows up as a basic bluish colour with a little light red, while birch, already fully in leaf, has a saturated bright red colour. The images of all species turn a darker red from mid- to late summer (lower diagram). No stems or branches are seen and the reflections from the old foliage are about the same. The dashed line in Fig. 7 indicates that variation in colour may be due to the fact that the growing conditions differ in moisture content. Birch exhibits different colours depending on the moisture content of the site on which it grows; a dry location gives a bluish colour, while a mesic or moist one gives a bright red one. These colour differences give rise to quite different possibilities to interpret deciduous trees with high accuracy, as the structure is consistent during the vegetation period (Ihse 1978). The colour of coniferous trees is shown for comparison. These trees do not change much during the vegetation period, and they are always much darker than any of the deciduous trees.

It is thus only for a rather short period that colour is a good indicator for distinguishing deciduous trees. The colour indicator must consequently be combined with other indicators to identify deciduous trees during most of the vegetation period. The most important indicators are structure and site or habitat. Structure can be described by the size, shape and profile line of the canopy, and the pattern of branches, together with the average height of the crowns shaping a more or less compact crown ceiling. The density of the canopy and its heterogeneity can reveal whether there are several generations of trees, even very old and dead ones, thus indicating high biological diversity. In addition, the habitat must be described by its topographical, geographical and ecological position (cf. Table 2). Only a few species can be distinguished on the scale used.

More than 10 types of different meadow can be distinguished in CIR aerial films. These can be summarized under three headings – dry, mesic and moist – according to the

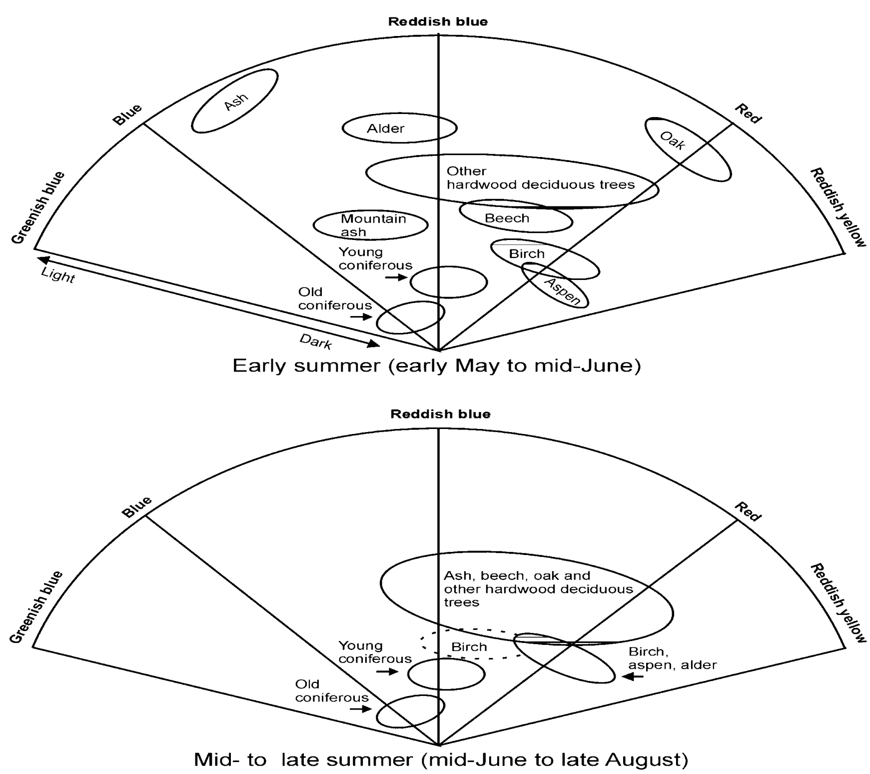

Fig. 7. Diagram showing varying possibilities for interpreting deciduous trees in CIR aerial photos during different vegetation periods when using colour as an indicator. The diagram shows colours of common tree species relative to each other in a sector of the colour circle.

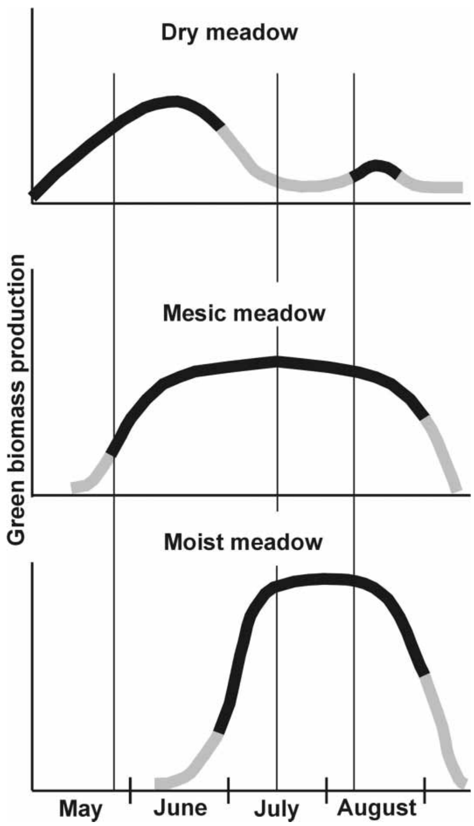

Fig. 8. Changes in colour in CIR aerial photographs related to biomass production and phenology during the vegetation period in dry, mesic and moist meadow vegetation in agricultural landscapes. The diagram also shows how the colours in the three meadow types change their relative order at three different times, early summer, high summer and late summer, as indicated by the vertical lines.

amount of soil moisture, which give different colours in different periods (Fig. 8).

As seen in the figure, dry meadows start their vegetative period early in May; they reach maximum production between mid- to end of June, when they begin to dry out quickly, and reach senescence in July, with a minor re-growth starting in August. Mesic meadows start the vegetative period later, but grow quickly, having high biomass production for a long period. The growing season of moist or wet meadows begins late, although they usually have a very high biomass production; they may wither away rather early (due to cold air assembling in the low-lying areas where they grow, with the consequent risk of early frost). In early summer the dry and mesic meadows are red due to the growing vegetation, while the moist/wet meadows are blue or whitish blue due to the large amount of dead vegetation from the previous year, or are bluish-green due to the wet substrate. In high summer, the colouring is reversed; the dry meadows are blue, due to the newly senescent vegetation, while both the mesic and moist meadows are red due to the growing vegetation. In late summer all three may be red.

In summary, to avoid introducing false changes in status descriptions and studies designed to detect change, accurate descriptions are essential; it is important to know exactly when the photos were taken in relation to the phenology of the species.

Vegetation and landscape changes

The changes found by CIR aerial photo interpretation are summarized in Table 4. The indicators used for mapping vegetation status and those used for change detection are summarized in Table 5.

Mountains have been under pressure from increased reindeer grazing and the impact of tourism, as well from the intense management methods practised in forestry during the past few decades. This is most obvious in subalpine and low alpine areas. The most important vegetation type in low alpine areas, dry dwarf shrub and lichen heaths dominated by *Empetrum hermaphroditum* and *Cladonia* and *Cladina sp* lichens, is very sensitive to trampling and the impact of off-road vehicles. Damaged and changed vegetation was found in different areas of the mountains. It showed up in the decreased lichen and vegetation cover. Damage to the vegetation cover is always especially critical in mountainous areas, as it entails a high risk of erosion. Damage to the lichen cover is also critical. Lichens are a very important species for the functioning of many boreal and arctic ecosystems, since they regulate albedo (with high light reflectance), preserve soils from wind and water erosion, and regulate moisture conditions. Changes in mountain vegetation have been studied by Ihse & Allard (1995), Allard et al. (1998), Nordberg & Allard (2002). They found that the amount of lichen had decreased during a 15-year period in nearly all of the areas investigated, by as much as 40% in some areas. The number of places in which erosion had caused vegetation to deteriorate or disappear had increased by 70% in some test areas.

An increase in tree growth was found in *mires*. Most of the raised bogs are encircled by a narrow belt of pine trees, but these have now expanded into the centre, which was previously treeless. In test areas in 12 southern Swedish mires the increase in tree cover was nearly 20% during a period of 40–50 years. In the Aneby mosse, the tree cover increased from 14% (covering 12 ha) in 1950 to 44% (covering 36 ha) in 1993 (Leine 1999). In some of the mires investigated we also found changed dominance of species, increased hummock vegetation and changed hydrological patterns, where parts that were formerly wet had dried out. The changes that were registered indicate that a change has taken place in the function of the ecosystem as well as in biodiversity. Changes in mires have been studied in high resolution scanned black and white aerial photos, with overlay analyses in GIS Arc/Info. The CIR photos have been used to interpret the vegetation types. (For a full description, see Ihse et al. 1992; Leine 1998; 1999).

Table 5 shows that the indicators and classes used for the mapping and status description of vegetation must be complemented for monitoring and change detection. The Table also shows that many types of vegetation exhibited no apparent change during the 15-year period studied.

The changes apparent in the *agricultural landscapes* are mainly due to the decrease and fragmentation of grasslands

Table 4. Important vegetation and biotopes sensitive to environmental changes in selected ecosystems, detectable by CIR aerial photographs.

Ecosystem	Sensitive vegetation and biotopes/elements	Expected changes	Detected changes in CIR-aerial photos
Mire	• pine/birch trees fen/bog • limit hammock-hollow • small-scale structures drainage patterns	• increased tree growth • increased hummock-vegetation • disappearing string-structures • changed hydrology	• increased tree growth
Mountain	• vegetation cover • lichen • bedrock-bare soil • dry wind-blown heath • Salix shrub • Fen	• decreased lichen cover • decreased vegetation cover/bare mineral soil • soil erosion • changed vegetation composition • changed drainage in mires • insect-damaged forest • hard-grazed shrub • higher tree limit • denser forest	• decreased lichen cover • decreased vegetation cover/bare mineral soil • increased soil erosion • dead vegetation, increased areas of dry dwarf shrub heath • insect-damaged forest
Agriculture landscapes	• old deciduous trees • dry grasslands • wet grasslands • open water • fen • small linear and point biotopes	• decrease of grasslands • decrease of wetlands by drainage • decrease of old deciduous trees • fragmentation of grasslands • tree plantations on field • lost connectivity corridors interrupted	• decrease of grasslands • decrease of wetlands by drainage • decrease of old deciduous trees • fragmentation of grasslands • tree plantations on field • lost connectivity, connecting zones interrupted
Forest key biotopes, forest vitality	• key biotopes • old forest • dead wood • deciduous trees • wet forest • steep slopesdefoliation • discoloration	• not studied	• used indicators for status description • heterogeneity of stand age and composition • amount of old forest/trees • amount of dead wood • changed pattern and age of deciduous trees • defoliation • discoloration

and wetlands. A summary of the indicators used for mapping status and changes in the agricultural landscape is given in Table 6. The changes in the agricultural landscape may be summarized as:

- Increase in the size of fields.
- Decrease in agricultural land area.
- Decrease in grasslands, meadows and pastures, both in size and in number.
- Decrease in the number of small point biotopes, (habitat islands and ponds).
- Increase in the length of small linear biotopes (road verges, stone walls, hedges, water courses, and ditches).

The decrease in the area of agricultural fields has occurred because coniferous trees, mostly spruce, have been planted in many fields; the area of grasslands has decreased because they have been ploughed, or because bushes and reeds have been allowed to encroach, or because spruce has been planted. Those fields that still exist have increased in size and their shape is more regular, with fewer curved boundaries and thus shorter ecotones towards the forest edge. The structure of the landscape has become larger in scale and more coarse-grained, while both the length of linear elements and the number of point elements has decreased (Ihse 1987; 1995; 1996; Ihse et al. 1991; Skånes 1996; Ihse & Blom 2000). The changes in the agricultural landscape during the past 50 to 60 years have been recorded on maps (Ihse 1995).

The quantification of the changes that have occurred is not the aim of this paper, but I will give a few examples from the study areas to show the extent and rate of change, thus exemplifying the type of detail is possible to obtain with this method. Both areas and numbers of objects are important to register from a landscape ecological point of view. In the Svenstorp area where a 30-year period was studied (from 1947 onwards), the dominating increase is in the mean size of the agricultural field, which increased by 500%. In all other landscape elements there was a decrease: the length of road verges decreased by 41%, the length of open ditches and water courses by 50%, and the length of the stone walls by 40% (Ihse & Lewan 1986).

In the Ystad area the total grassland area (meadows and pastures) decreased by 50%. The number of grassland patches decreased only by 35%. The wetlands, which were found as many small patches, became nearly extinct, decreasing by 94% (Bengtsson-Lindsjö et al. 1991). In the Tomteby area the fragmentation was clearly documented, as three large continuous areas of semi-natural grasslands were fragmented into 29 small patches. The extent and rate of decrease were about the same in all study areas, concerning small biotopes of linear and point objects, varying between 0.3% and 2.5% per annum in the same period.

Table 5. Overview of interpretation criteria in CIR aerial photographs used to describe vegetation status and changes in mountain vegetation in Sweden.

Actual mountain vegetation		Changes	
Vegetation types	Criteria to define actual vegetation	Criteria to define changes	Type of changes found in field
Bare rock, block field	Colour, texture, altitude	None	Newly exposed areas without crust lichen
Snow beds	Colour, texture, soil moisture, position	None	None
Extremely dry dwarf shrub heaths	Colour, topographic position, altitude	Colour (changed hue from greyish blue to intense blue), size (increased), vegetation density(decreased)	Dead branches, exposed mineral soil, decreased vegetation cover, soil erosion
Dry dwarf shrub heath with mosses	Colour, texture, topographic and ecologic position, altitude	None	Increased amount of grasses
Dry dwarf shrub heath with lichen	Colour, texture, topographic and ecologic position, altitude	Colour (changes into different blue hues), texture (changes into coarser)	Crushed lichen, decreased lichen cover, decreased vegetation cover, bedrock and mineral soils, soil erosion
Mesic dwarf shrub heaths	Colour, texture, vegetation density, vegetation height, topographic and ecologic position, altitude	None	Frost-damaged leaves, dead branches
Wet shrub heath	Colour, texture, vegetation density, ecologic position, soil moisture	None	None
Grass heath	Colour, texture, vegetation density, altitude, topographical position	None	None
Meadows, dry-mesic low herbs	Colour, texture, vegetation density, ecological position, altitude	None	Decrease of herbs, increase of grasses, increased number of reindeer paths, soil erosion
Meadows, mesic-moist, high herbs	Colour, texture, vegetation density, ecological position, size, altitude	None	None
Fen and mires	Colour, soil moisture, ecological position	None	Decreased vegetation cover, exposed peat in tracks and paths, soil erosion
Willow shrub	Vegetation height, colour, texture, ecological position, shape and size	None	Defoliated branches
Birch forest heath type, lichen rich	Vegetation height, colour, vegetation density, altitude	Colour, texture, vegetation density	Decrease of lichen cover, dead and defoliated trees from insect attacks
Birch forest heath type, moss rich	Vegetation height, colour, vegetation density, altitude	Colour, texture, vegetation density	Dead and defoliated trees from insect attacks
Birch forest meadow type	Vegetation height, colour, vegetation density, altitude, bedrock type	None	Dead and defoliated trees from insect attacks

Accuracy in classification

Accuracy, evaluated as a comparison between the interpreted vegetation classes and the field controlled classes, is high, over 80%. This is true of most of the ecosystems investigated. Classification on general levels gives a higher degree of accuracy than detailed mapping using more classes, as can be seen in Table 7.

Fig. 9 shows the differences in the accuracy of interpretation of various groups of deciduous trees registered by CIR aerial photography at different periods. Applying this knowledge to photographs taken in late spring gives a much improved accuracy of interpretation. A comparison between the interpretation of photographs taken in late spring (end of May) and high summer (beginning of August) shows an increase in accuracy in late spring of nearly 20 units, nearly 90% instead of 70% (Ihse 1978). Oak can easily be distinguished from other deciduous hardwood species, (ash and beech), and birch and alder can be distinguished from other deciduous softwood species (aspen, mountain ash and others). The accuracy of this interpretation is approximately 15–20% higher in early summer than it is in high or late summer, mainly because of the good colour differentiation in early summer (cf. Fig. 7). Compared with interpretation using black and white aerial photos, CIR aerial photographs still have a 15% to 45% higher degree of accuracy.

CIR aerial film on a scale of 1:30,000 is the most suitable for both medium-scale and detailed mapping. CIR aerial film on a scale of 1:60,000 is suitable for medium-scale mapping. Black and white film on a scale of 1:30,000 does not give enough information to distinguish between various types of vegetation for general vegetation mapping, as it has an overall accuracy of less than 70%. The indicators used here would probably change considerably if larger scales, such as 1:10,000, were used. In our tests we found that using this large scale gave no advantages other than in detecting damage to forest, in which case the structure of each individual tree must be investigated. Another advantage of using medium- and small-scale pictures and an interpretation instrument with high magnification is that it is cheaper, as the area photographed will increase fourfold when the flight altitude is doubled (from photos on a scale of 1:30,000 to 1:60,000). Some examples of the possibility to use CIR aerial photos to distinguish vegetation types from different phenological periods, and their connection with physical geographical parameters and land-use are given in Fig. 10.

The rate of mapping is high when compared to field inventories. For mountain vegetation, the rate of mapping when interpreting CIR aerial photos is approximately 10 times higher than for field mapping. On average we have interpreted approximately 10 km^2/hour, which corresponds to 50 km^2 per day. In comparison, the rate in field mapping is

Table 6. Summary of interpretation criteria for vegetation status and changes for vegetation in agricultural landscapes, found in CIR-aerial photos. Overview of indicators in CIR aerial photographs used to describe vegetation status and changes in agricultural landscapes in Sweden.

Actual vegetation		Changes	
Vegetation types	Indicators to define actual vegetation	Indicators to define changes	Type of changes found in field
Agricultural fields	Shape, size, pattern, cover, colour, texture	Pattern (small dots, large stripes), texture, colour	Small parts excluded, abandoned field, plantation of coniferous trees, encroached by bushes
Cultivated grasslands	Colour, shape, boundary, cover, texture, site	Colour, texture	Ploughed to crop field, encroached by bushes, planted with trees
Semi-natural grasslands, dry (several types)	Colour, cover, texture, topographical position, exposition, landscape position	Colour, texture, height	Fertilized, planted by trees, encroached by juniper, thorny bushes
Semi-natural grasslands, mesic-moist-wet (several types)	Colour, sites, soil moisture, height	Colour, texture, height, pattern	Encroachment of reed, of bushes and trees, (alder, willow), ditched and drained
Semi-natural heaths (several types)	Colour, geographical position, soil type, texture	Colour, texture, pattern	Increase of heather on grassland, encroachment of deciduous trees (birch, aspen), plantation of coniferous trees, decrease of grazing, erosion by trampling
Wetlands, fens (several types)	Topographical position, sites, shape and size, colour, pattern	Colour, pattern	Drained to mesic/wet grasslands, encroached by bushes and trees
Semi-open wooded pastures (several types)	Pattern, density, height, shadow, colour, size, crown size and profile	Colour, pattern, density	Increased cover/growth to dense forests
Shrub/bushes (thorny, deciduous, juniper)	Height, colour, texture, sites, size	Cover, texture	Increase of amount of bushes and cover, clearance of bushes
Deciduous woods and forests	Colour, height, tree density, crown size	None	None. When clear cut the vegetation resembles semi-natural grasslands
Coniferous forests	Colour, height, tree density, texture	Colour, texture	Depending on management methods and age
Urban buildings and infrastructure	Colour, pattern, size, shape	Colour, pattern, size, shape	New or demolished buildings, new roads

5 km^2 per day. In agricultural and forest landscapes at the general level, using approximately 20 classes in the classification system, the rate is 50–80 km^2 per day (5–10 km^2/hour), and for detailed mapping, using approximately 50 classes or more, 10–20 km^2 per day (2.5 km^2/hour). This should be compared with field mapping in this terrain, which covers *c.*2 km^2 per day (Ihse & Wastenson 1975; Ihse 1978).

Discussion

Disadvantages and advantages of stereo CIR aerial photographs

In landscape ecology today, different types of remote-sensed data are the main tools for collecting data and analysing the landscape. When high quality (resolution) spatial information is needed, aerial photography is still the main tool for obtaining a high degree of accuracy. The new, very high resolution satellites, such as Ikonos, which have so far been tested only in a few areas, cannot yet give the same information in practice, and the cost is much higher (Groom et al. 2006).

This study is primarily based on CIR films, but as this film type has only been in use since the beginning of the 1970s, black and white photos still have to be used to study the changes that have taken place in the agricultural landscape over a longer period ($\sim$60 years). The main advantages of CIR aerial photography over black and white photography when mapping vegetation can be summarized in seven points. On CIR aerial film it is possible to 1) identify a larger number of different types of vegetation, 2) distinguish clearly between coniferous and deciduous trees, 3) differentiate between several moisture regimes, 4) differentiate between various

Table 7. Summary of accuracy in interpretation compared with field classification, in different ecosystems.

Ecosystem/landscapes	Interpretation accuracy: Generalized level (no of classes)	Interpretation accuracy: Detailed level (no of classes)	Reference
Mountain, status	95% (6 classes)	87% (16 classes)	Ihse & Wastenson (1975)
Mountain, changes	99% (6 classes)*	81% (11 classes)**	Allard et al. (1998)
Mires	95% (5 classes)	82% (14 classes)	Rafstedt & Andersson (1982)
Agricultural, open areas, patches	83% (11 classes)	74% (19 classes)	Ihse (1978)
Agricultural, linear and point elements	97% (15 classes)	97% (25 classes)	Cousins & Ihse (1998)
Forest	87% (11 classes)	76% (23 classes)	Ihse (1978)
Forest, key biotope elements	73–75% (7 classes)		Löfvenhaft & Ihse (1998)

* wind heaths ** lichen cover

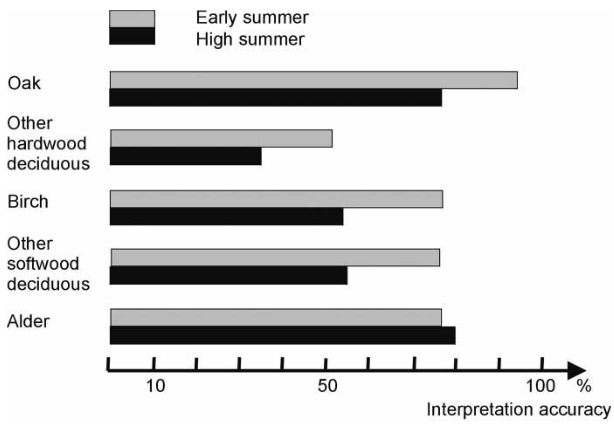

Fig. 9. Accuracy in identification of deciduous forest biotopes at different times.

layers of vegetation in forest, 5) differentiate between dead and living vegetation, 6) differentiate between substrate constructions and living vegetation, and 7) define structure and pattern with higher contrast.

Types of vegetation can be distinguished from each other due to their basic differences in spectral reflection, which produce the different colours in CIR aerial photographs. The spectral reflection is not only dependent on the type of species but is also influenced by a number of other vegetation factors, the most important of which are structure and texture. As shown here, other indicators apart from spectral reflectance are of importance in obtaining a high degree of accuracy in the interpretation. They can be related to ecological conditions, physical features, topographical and geographical position, as well as present-day and historic land-use. A combination of spectral reflectance and the other indicators have been used to achieve good classification in the types of vegetation studied. Bastian (1999) describes the same type of approach in a description of aggregated or compound indicators for other types of vegetation and classes. A good knowledge of the object studied both in the field and in photos is essential, and helps to develop fresh insights into new fields. An example of this is to be found in Ask & Nilsson (2004), who used forest-stand characteristics in an interpretation of CIR aerial photos and detected a high correlation with red-listed (Gärdenfors 2005) species of epiphytic lichens.

One general feature in aerial photos, of importance to vegetation mapping and monitoring, concerns the geometric characteristics of aerial photos. The effects of central projection are well known and have been described in many textbooks on the interpretation of aerial photos. However, there are some features linked to this phenomenon that may be of specific interest for vegetation mapping. Some of the examples highlight advantages for interpretation, others highlight disadvantages. The same object will be a different size and shape in different parts of the photo. This shows up particularly clearly in forested or sparsely wooded areas. A tree in the central part of the photo looks like a dot; trees in peripheral parts, however, are seen in an oblique view and look more like the shape we are used to seeing in the field view. Because of the specific shapes of shadows, they can also be used for classification as long as there is enough open space around the tree or forest to make the shadows clear and distinct. The shadow of a spruce looks like a triangle and that of a pine like a lollipop.

Displacement and shadows hide the ground, which can lead to false or undetected changes in the field layer. This is evident when working on single images, particularly if the selected object is not situated in the same position when comparing two photos taken at different times. Stereo viewing gives an increased gradient for slopes, exaggerating height. This is important for change detection. It is also important to be able to use indicators associated with topographical position, for example different moisture regimes and settlement sites. In evaluating accuracy with the aid of matrixes, some features stand out as being easier to interpret, while others are more difficult.

Change detection and monitoring

According to Antrop (1998) and also Coppin & Bauer (1996), the following questions must be asked in change studies: a) what is changed, b) what is the frequency of the change, c) what magnitude has it, and d) what time scale should be used?

In working with CIR aerial photos these are highly relevant questions. The changes found must also have plausible and ecologically sound explanations. However, to discuss the causes and drivers of the changes is not the purpose of this paper. Nevertheless, expected changes could be used as a hypothetical basis for looking for changes in the photos due to known causal relationships.

The indicators and classes used for status description from the CIR aerial photographs need to be developed, or new ones must be found, in order to study changes or to locate areas of high biodiversity. This is especially true of mountain vegetation and key biotopes in forests. In mountain areas, two parameters can be used to show changes in how the ecosystem is functioning; a decrease in lichen cover and an increase in the number of erosion spots on mineral soil. The level of generalization in ordinary vegetation maps (Rafstedt 1984; Andersson et al. 1985) makes it impossible to follow these changes. These maps were originally designed for planning purposes regarding nature resources and nature protection. Other changes detected in the field, such as small tracks made by off-road vehicles in mires, or defoliated trees and bushes, could not be detected in CIR aerial photos on a scale of 1:60,000. A summary of the methods used for monitoring mountain vegetation is given in Ihse et al. (1999).

The same indicators can often be used for agricultural landscapes, both for status mapping and to detect change. In detecting change it is important to include small biotopes with linear and point elements. Sudden changes such as the following are easy to detect: a) exploitations for roads or buildings, b) seasonal changes in management methods, such as new open ditches, newly ploughed grasslands, and new fences where different management methods have been employed on either side. More difficult to detect are slower changes, such as a) increased management intensity in grazing or mowing, or abandonment leading to changed species in the field layer or increased tree- and bush- density in wooded

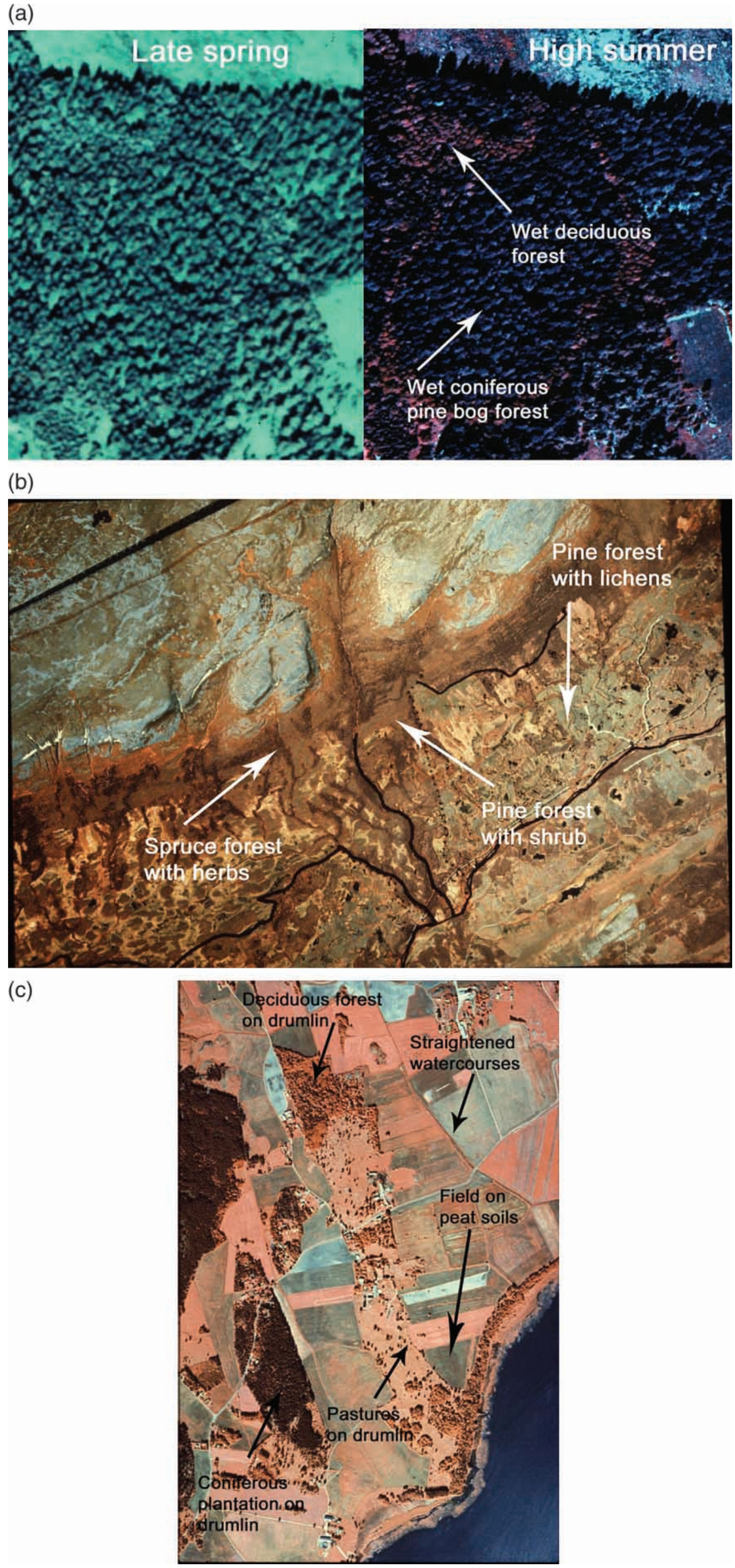

Fig. 10. Some examples from CIR aerial photos of the possibility to distinguish different vegetation types of a) coniferous forests and field types, b) differences depending on different photo and phenological periods, and c) the connection between vegetation types, physical geographical parameters and land-use (Courtesy of the National Land Survey of Sweden).

pastures, b) changed nutrition gradients, c) new plantations of coniferous trees in agricultural fields, d) changed soil moisture due to ditching and drainage and e) details such as cattle tracks and other narrow linear elements. Some classes or parameters that are easy to distinguish in the field cannot be detected or can be detected only with only a low degree of accuracy in interpretation: for example, different types of crops, fertilized grasslands versus semi-natural grasslands, the recent encroachment of bushes and transition zones on the edges of forests.

Distinct methods have been used for monitoring different parts of the Nordic landscapes, and intense methodological development is still taking place, as summarized by Groom & Reed (2001). Especially when making serial time change measurements, changes may occur as pure artefacts due to differences in personal experiences and skills rather than real changes. If the classification systems and the interpretation indicators are clearly defined and the interpreters trained with common reference area, this will not be a serious problem. Allard (2003a) tested accuracy in repeated interpretation of the same interpreter, with very good results, with an accuracy of 98%. Ihse (1978) found only minor divergences between two experienced interpreters. Lindblad (2007) found that automatic classification generated higher differences between different methods, from automatically classified digital CIR aerial photos.

Integrating landscape structure

When considering agricultural and urban areas, it is important to include landscape structures in the analysis of landscape and change, in order to fully understand the influence and importance these changes have on biodiversity, or in order to find potential areas with high biodiversity value. Although several landscapes indices are available and their use and importance have been discussed in the literature, none have been found that could be used in a general manner. In Sweden, the method of separately mapped patches, lines and points (PLP method) is used for collecting landscape data and for facilitating an understanding of landscape structure and its relation to landscape ecological principles (Ihse 1996; Ihse & Blom 2000). The main landscape changes detected by aerial photo interpretation in Sweden are intensification in central areas and abandonment in marginal areas. Fragmentation and isolation are essential landscape characteristic changes. Intensification often means fragmentation and isolation, observable as a simplification in shape and form as well as in ecological infrastructure; marginalization means the encroachment of bushes and spruce plantations.

Relations to biodiversity and ecosystem functions

Both intensification and abandonment in agricultural landscape entail a risk of decreased biodiversity. As the ecological infrastructure diminishes, there is less potential for dispersal and rich habitats decrease in number and area. In marginal areas, abandonment is ongoing, entailing reforestation, plantations and the encroachment of bushes. Formerly continuous grasslands and open agricultural areas are fragmented by forests. This leads to a decreased number of potential areas of high biodiversity. The change from open grassland to dense spruce plantation also leads to a shift in the function of the ecosystem.

In some studies, in order to describe the effects of the changes, these landscape changes have been associated with the changes in abundance of selected animals, plant groups or species (Robertson et al. 1990; Bengtsson-Lindsjö et al. 1991). This basic material can be used to understand drivers and to analyse the effects of change. The potential of the CIR aerial photos also makes it possible to easily collect new types of landscape data.

Interpretation indicators for CIR aerial photographs have been developed for both coniferous and deciduous forests to describe potential high biodiversity, and have been tested using lichens and mosses. These indicators, which are not the same as those used to describe vegetation and field classes, consist of factors such as tree species, and tree age, height and width, and include certain vegetation types and an overall heterogeneity in the canopy.

The methods described here have been adapted to Scandinavian conditions and the results can thus only be applied here. The approach used to identify interpretation indicators and to classify vegetation, habitats and landscape elements in different landscapes, and vegetation in different climatic zones, is more generally applicable.

Conclusions

The spectral resolution of CIR aerial photographs is most useful for mapping present-day vegetation and its status, as well for detecting change during recent decades, and for monitoring indicators of biodiversity and landscape qualities in general. Especially important in temperate climatic zones is the ability to differentiate clearly between deciduous and coniferous trees and between living and dead vegetation, as well as between substrate and vegetation. In addition, it is important to be able to distinguish soil moisture types.

For high accuracy in mapping and monitoring from CIR aerial photographs, the following conditions need to be fulfilled:

- Negative scales must be such as to give high topographic differentiation and high spatial resolution and the photos must be repeated in relevant time sequences.
- Stereo pairs need to be used both in the laboratory and in the field.
- Zoom-instruments with a high degree of magnification are necessary, as this makes it possible to use different magnifications for different interpretation indicators. Photographs with high resolution are also necessary.
- Classification systems must be adapted for the aim, the film type, and the scale, and need to include a feedback loop after field controls.
- Interpretation must be an integral part of an approach that consists of several steps.
- Colour is the most important interpretation indicator, but it cannot be used alone.
- Classes must be identified using a complex system of interpretation indicators, including spectral reflection

(colour, hue and intensity), physiognomy (texture, vegetation density, vegetation height), ecological conditions (soil moisture, nutrition status), species (only dominating or with high vegetation cover), site (geographical position, ecological position, topographical position, exposure), substrate (bedrock, soil type, geomorphologic form element) and anthropogenic influences, constructions and management (ditching, ploughing, tree plantation, grazing, mowing, fences and hedges, buildings, roads).
- All mapping and monitoring must be combined with fieldwork. The easiest and most effective method of doing this is by making transect inventories.

Finally, the 'archive value' of the CIRs is high and the archives need to be safeguarded as a database over a critical section of the world, in terms of global change research, and in order to fulfil the eventual necessity to continue a monitoring scheme using either CIR or comparable remote sensing techniques.

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