TOWARDS AN UNDERSTANDING OF UNCERTAINTY IN GREENHOUSE FOREST ASSESSMENTS

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ABSTRACT:

Australia's National Carbon Accounting System provides information on land-based sources and sinks of greenhouse gases to fulfil international reporting obligations under the Kyoto Protocol, as well as providing annual estimates to Australia's National Greenhouse Gas Inventory. Manifold is an understanding of change in forest area: afforestation, reforestation and deforestation events. Using a thirty-year archive of Landsat imagery (1972-2002), a set of 12 continent-wide land cover maps, and associated change layers for the 11 intervals was created. A continuous probability network was then used to estimate the probability of a pixel belonging to Forest or Non-Forest classes for each of these 12 dates. These Forest/Non-forest classifications, from successive dates, were then compared on a pixel-by-pixel basis to identify areas of No Change (Forest), No Change (Non-forest), Deforestation, and Regrowth. To gain an understanding of the uncertainty in these change maps, and so that improvements could be made in the mapping technique, a fuzzy evaluation methodology was developed and implemented. A network of ~300 aerial photographs was co-registered to the database and more than ~12,000 points were compared using photo interpretation to validate the matching pixels on each respective change map. The classes used for the photographic interpretation were Definitely Forest, Probably Forest, Unsure, Probably Non-forest, and Definitely Non-forest. Australia-wide the error rates were very low. The 'definite' errors for forest were ~2% and 'definite' errors for non-forest ~4%. Hotspots of uncertainty in forest change errors did emerge however in some forested areas (up to 5.7%). To improve the temporal classification process, a performance analysis was undertaken that cross-referenced reported change in forest area with reported errors in classification. This process will be repeated with each continent-wide land cover map update to provide progressive improvement in the change maps.

1. INTRODUCTION

1.1 Background

Article 4.1(1) of the United Nations Framework Convention on Climate Change (UNFCCC) commits Australia to produce an annual inventory of national greenhouse gas emissions according to the Revised 1996 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories[1]. The inventory reports human-induced greenhouse gas emissions, by sources and removals by sinks, not controlled by the Montreal Protocol, in six sectors: energy, industrial processes, solvent and other product use, agriculture, land use change and forestry. Reducing the levels of uncertainty previously associated with estimates of land use change emissions is essential as they are a significant component of Australia's greenhouse gas emissions profile. In 1998, to achieve the above, the Australian Government commenced the development of its National Carbon Accounting System (NCAS).

Fundamental to accounting for carbon change in land use is an understanding of the change in land cover. The impact of an event associated with land cover change may continue over many years and vary with time since the event took place. It is, therefore, necessary to monitor change in land cover over extended periods of time. To be considered in the NCAS accounting framework, the land cover change must also be shown to be directly human-induced, that is a deliberate, not an indirect natural event (Furby, 2002).

1.2 Continental Database

Landsat data were used to create a continent-wide (Australia including Tasmania) database of Forest / Non-Forest Landcover for 12 time periods, spanning 1972 to 2002 (1972, 1978, 1980, 1985, 1988, 1989, 1991, 1992, 1995, 1998, 2000 and 2002). Forests are defined as having a minimum of 20% tree crown cover and a minimum height of 2 metres at maturity. A

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1 United Nations Framework Convention on Climate Change, Article 4, para. 3.

minimum area of 0.2 hectares is also imposed (Richards and Furby, 2003). Given the size of Australia (690 million hectares) ~370 Landsat Thematic Mapper (TM) scenes were required for complete coverage for a single date. Where continent-wide coverage was available for a given date (1989 onwards), TM data were acquired; for dates prior to this, Landsat Multi-Spectral Scanner (MSS) data was acquired.

For continent-wide image registration, the 2000 imagery was first geometrically corrected using reference maps and a digital elevation model (DEM), and mosaic'ed to produce a geographic reference base for the entire imagery set (Furby, 2002). Imagery for prior dates was then co-registered to this 2000 geographic rectification base. During this process, TM images were resampled to 25 m pixels and MSS images were resampled to 50 m pixels. For radiometric correction over a multitude of dates, an invariant target correction approach was adopted (Furby and Campbell 2001). This corrected for sun-angle and earth-sun distance and employed a bi-directional reflectance distribution function (BRDF) for surface properties correction (Danaher *et al*. 2001).

The continent-wide mosaic was separated into 37 1:1,000,000 map sheets, which are employed by various federal agencies for mapping Australia. Each map sheet was stratified into areas that were known to have soils or other characteristics that would affect the spectral identification of forests. For each stratum, a series of vegetation indices were formulated and evaluated to determine their capacity to distinguish between Forest and Non-Forest. Thresholds for the selected indices were then calibrated and chosen using training samples to assign a given pixel to one of three classes: Forest, Non-Forest and Uncertain (Furby and Woodgate, 2001). The classification of the Uncertain pixels for all pixels and all dates was resolved using a continuous probability network (CPN -- Cacetta 1997). The CPN examined the temporal pattern of the probabilities derived from the indices while recognising that different change classes have distinct temporal patterns to their probabilities (Figure 1). In this manner, Uncertain areas were assigned to either the Forest or Non-Forest classes to produce the final maps for each date.

Change maps were derived from this temporal sequence of classified satellite images. Since there are 12 (multi-temporal) images associated with any given area, up to 11 change maps can be produced by comparing sequential pairs of images covering the period from 1972 to 2002. Temporally, each pixel can then be classified based on the changes that have occurred over the entire period 1972 to 2002. Five classes were identified as follows.

- Non-Forest throughout - NFT.
- Forest throughout -FT.
- Non-Forest that became Forest and remained Forest - REG(rowth).
- Forest that became Non-Forest and remained Non-Forest (deforestation)- DEF.
- Forest or Non-Forest that changed to Non-Forest or Forest respectively, and then back to Forest or Non-Forest one or more times - CYC(lic regrowth).

2. METHOD

2.1 Validation

In the context of remote sensing 'validation' is the process of assessing by independent means the accuracy of data products (Justice *et al*., 2000; Privette *et al*., 2000). In general, validation refers to assessing the uncertainty of satellite-derived products by analytical comparison to reference data (e.g., *in situ*, air-craft, and high-resolution satellite sensor data), that are presumed to represent the true values (Justice *et al*., 2000). This is often achieved using a confusion matrix. A confusion matrix is developed by sampling a sub-set of pixels from the classes present on a classified image, obtaining better quality "reference data" for each pixel, and cross-tabulating the sample pixels. A variety of summary information can then be extracted from this matrix – e.g., kappa (Cohen 1960), and user's and producer's accuracy (also known as errors of omission and commission) (Congalton 1991). The use of a confusion matrix implicitly assumes that one has reference data that provide a definitive land classification for each pixel. Gopal and Woodcock (1994) note that this is rarely the case, and also that even in the presence of definitive reference data, all classification errors are not equally incorrect – e.g., confusing a lake with a swamp is less serious than confusing a lake with a forest. They therefore propose a fuzzy method of image classification accuracy assessment that implicitly addresses the uncertainty inherent in assigning a point to a single class using the reference data, while also addressing the magnitude of the difference between the most likely reference data class and the image class. Foody (1996) notes that while "hard classifications" are employed in most mapping methodologies and products, "soft classifications" may be more appropriate when evaluating the classification of digital imagery. This is due to the presence of mixed pixels (mixels, particularly at the interface of two landcovers) and the fuzziness of *in situ* observations.

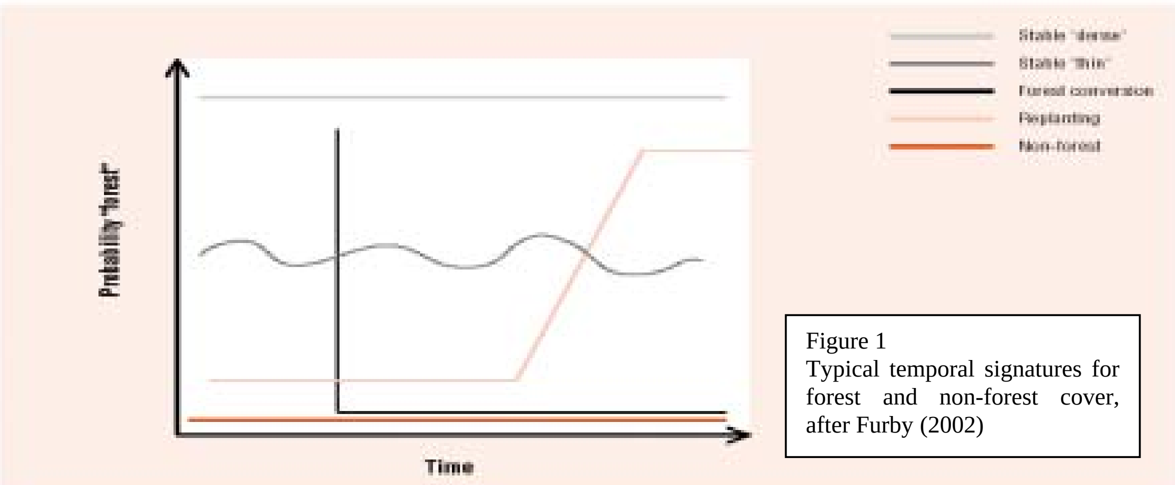

Figure 1
Typical temporal signatures for forest and non-forest cover, after Furby (2002)

2.2 Continuous improvement protocol

The National Carbon Accounting System considered evaluating the quality of the change maps critical to the monitoring process. The goal of this evaluation was two-fold. Firstly, to assess the quality of the change maps; and secondly, to identify reasons why the change maps appeared to have problems so that the classification procedure(s) could be continuously improved.

The continuous improvement protocol was initiated in 2001 after completion of the first 10 change maps. Subsequently, some of the map sheets were revised and the classification methodology amended for the 11^{th} change map production (2000-2002). Continuous improvement responds to the ongoing development and updating of the NCAS land cover program by looking at the source and significance of potential errors. This allows for a targeted and prioritised rectification of any problems that can be assessed and, if necessary, further amended on each round of updating and continuous improvement. In contrast, verification only provides a one-off statement of accuracy.

Initially, a traditional approach to accuracy assessment was envisaged whereby area-based samples would be extracted from a given change map, and concurrent areas extracted from higher resolution reference data for dates "close to" those of the satellite imagery used to produce the change map. As an alternative, it was proposed that enough points – rather than areas –be extracted from the change maps and verified against the reference data to allow a statistically valid statement of the accuracy of change maps to be produced. The area-based approach (e.g., Tian *et al*, 2002) finds its strength in a quantified statement of accuracy of areas of change, albeit qualified by the unavoidable difficulties of geo-rectification and the interpretation of differing image products. The suggested point-based method is more targeted at determining how good the current methodology for detecting land cover change from multi-temporal satellite images is at discriminating between Forest and Non-Forest conditions under a range of different circumstances (forest types, soil types, relief changes, etc.) and to testing the robustness of the methodology employed across the diverse landforms of Australia.

Verification of state (Forest/Non-Forest) and change map accuracy was accomplished by first verifying the existence of *suitable* high-spatial resolution images for a given change map area. Given the 30-year temporal scale, the best suited imagery were usually aerial photographs, with a spatial scale of around 1:50000, whose acquisition date were co-incidental or close to the satellite image acquisitions. These three factors – the region covered, the image scale, and the acquisition date –vary with each change map area. In total 384 aerial photo pairs were used in the verification; the majority of photos had scales between 1:25000 and 1:80000. Both panchromatic (black & white) and colour aerial photos were used.

Aerial photographs were the only data that could be employed as the reference data against which change maps would be assessed; no other information source was available nationwide from 1972 to 2000. A nationwide inventory was made of aerial photographs that were readily available from government agencies and their location relative to the 1:1,000,000 map sheets was noted. Where possible, 10 stereo pairs of aerial photographs were selected for each map sheet. In the more remote areas of Australia, it was sometimes not possible to obtain this many; 24 of the 37 mapsheets evaluated used 10 stereo pairs and 13 used fewer than this number. Photographs were selected based on their geographic and ecological distribution within a map sheet, their temporal distribution over the 30-year period, the scale and film type of the photograph, and the quality of the photographs.

Each of the 37 map sheets was evaluated individually and all map sheets were processed in an identical fashion. Each aerial photo was then gridded and converted to digital format and co-registered to one of the satellite images used in developing the associated change map. In general, the rectified and calibrated 2000 TM image was employed for this purpose. However, in some cases where cloud cover was too heavy for the photo location on the 2000 image, or land cover changes between the photo date and 2000 required that the 1991 TM image be employed.

Forty randomly selected points were then located on each co-registered photograph. For each point, a photo-interpreter determined what was present using a fuzzy classification with five classes:

- Definitely Forest; (see definition below)
- Probably Forest;
- Unsure;
- Probably Non-forest; and,
- Definitely Non-forest.

Fuzzy Logic Definitions

Definitely Forest:
Where the photo interpreter has no doubt that both the corresponding points on the change map and the photo are forest. The confidence of the interpreter relates to their knowledge of the local area, the stereoscopic information available from the photography, the relatively close alignment in time between the photo and the satellite images used to compile the change maps.

Probably Forest:
Where the photo interpreter has expressed a good degree of confidence in the matching relationship between the change map and the aerial photo but some uncertainty exists. For example, i) making a judgement call as to whether a forest was 1.9 m or 2.1 m tall or had a 19% crown cover or the required 20%; ii) unambiguously resolving the exact neighbourhood of the point being checked due to heterogeneities in the forest structure; iii) a slightly longer elapsed time between aerial photo and the satellite image and subsequent

After interpreting all forty points for a photo, the interpreter determined their image classification for the relevant change map. For example, a 1998 photo would be evaluated against the 1998 change map that covered the period 1995-1998. If the date for a photo did not exactly match a time slice date, it was evaluated against the closest date – e.g., a 1997 photograph was still evaluated against the 1998 change map. In such cases, if deforestation had clearly occurred between the date of a photo and its satellite-image equivalent, the areas affected were not sampled, or a different photo was employed.

In addition, (s)he recorded if the at least four of the eight neighbours of the pixel in question were of the same type in order to be able to subsequently identify isolated pixels. Finally, the photo-interpreter examined the temporal profile of the sampled pixel to determine if it was always forest (Forest Throughout), always non-forest (Non-forest Throughout), deforested one time and remaining non-forest (Deforestation), regenerated one time and remaining forest (Regrowth), or was Forest/Non-forest more than once separated by a

Deforestation/Regrowth event (Cyclic). Qualitative statements, made by photo-interpreters, about photographic quality or the general misclassification of an area were also noted.

The photo-interpreter then selected 20% of the photographs for the map sheet (two photos if 10 were available for a map sheet) for the purpose of Quality Assurance (QA). The photos selected were to be typical of the map sheet evaluated and/or be somewhat difficult to interpret due to topography, sparseness or height of vegetation, spectral characteristics, etc. A different photo-interpreter then independently re-interpreted the photos used for QA using a different set of 40 randomly generated points. If the general conclusion for both photographs was the same – i.e., there was/was not a potential problem with the classification of the area covered by the photograph – results for the map sheet were communicated to the Australian Greenhouse Office. If the general conclusion was not the same, the reason for the differences was determined, and the photos reinterpreted by both photo-interpreters. In using such a QA procedure, a reasonable level of confidence was attributed to the general conclusion for a map sheet.

Results for each photograph were tabulated and then summarised by map sheet to provide an indication of the quality of the change map for a given map sheet and results were then summarised by state and for all of Australia (Jones *et al*., 2004).

3. UNCERTAINTY IN GREENHOUSE FOREST ASSESSMENTS

3.1 Results and Discussion

The aim of the continuous improvement protocol is to provide a methodology that evaluates the general problems in change map classification, and / or assesses if there are any problems with specific regions or strata. Presented here are the results for the state of Tasmania and Australia as a whole (Lowell *et al*., 2003; Jones *et al*., 2004). Tables 1 and 2 describe the photo-interpretation relative to the change classification. Table 3 provides temporal, or lineage, information. The first point of note is that few sample points fall into the Regrowth and Deforestation change map classes. In an assessment of "change" this may, at first, seem inappropriate. However, it is in reality of limited concern. Change (Regrowth / Deforestation) represents a difference in "state" (Forest / Non-Forest) between sequential images. An ability to determine the reliability of "state" for a single image will implicitly provide reliable "change" determination and vice versa. For example, if it is known that the amount of Forest is overestimated for all years, then the amount of Deforestation is likely to be underestimated.

Overall the classification for Australia (Table 1) is reasonably good. What was classified as Forest was definitely wrong for only 2% of the total Forest verification points. Non-Forest, Regrowth and Deforestation returned results with definite error rates of 4%, 10% and 9% respectively. Probably <u>and</u> definitely wrong error rates for forest are higher at 6%, whilst the average probably <u>and</u> definitely wrong error rates for all classes is around 12%. It is inappropriate to interpret this information as a determination of change maps being "accurate/inaccurate." In an absolute sense, one could argue that the classification is "good" since 93% of the Forest points are at least probably correctly classified and only 2% are definitely wrong. It is more difficult to argue that the classification is "bad" because only 66% of the Forest pixels are definitely correctly classified, since the uncertainty of "probably" correct is potentially attributable to the aerial photograph analysis and not the change mapping. The indefinite categorization "probably" is used to highlight areas of doubt in the image classification and possibly in the photo-interpretation, and where further data should be sought to determine the correctness of the classification. This provides an important guide to continuous improvement rather than only producing a verification statement.
In Tasmania (Table 2) the image classification accuracy is not

	Total Points	DF	PF	U	PNF	DNF	%Def. Wrong	%Prob.+ Wrong	%Prob.+ Right	%Def. Right
Forest	5085	3380	1365	31	209	100	2	6	93	66
Non-forest	7318	282	847	88	1186	4915	4	15	83	67
Regrowth	105	38	49	1	6	11	10	16	83	36
Deforestation	56	5	8	0	11	32	9	23	77	57
Total	12564	3705	2269	120	1412	5058	3	12	87	67

Table 1 Australia: Tabulation of sample point results by change class (36 map sheets)

	Total Points	DF	PF	U	PNF	DNF	%Def. Wrong	%Prob.+ Wrong	%Prob.+ Right	%Def. Right
Forest	277	152	93	0	23	9	3	12	88	55
Non-forest	83	2	2	0	42	37	2	5	95	45
Regrowth	3	0	2	0	0	1	33	33	67	0
Deforestation	5	0	0	0	2	3	0	0	100	60
Total	368	548	377	24	229	444	3	10	90	52

Table 2 Tasmania Tabulation of sample point results by change class (one map sheet – nine aerial photos)

Tasmania	Lineage Class[1]					
		FT	NFT	DEF	REG	CYC
Total Points	368	270	25	54	7	12
% of Total Points	100	73	7	15	2	3
Definite Errors	12	8	2	0	1	1
% of Total Definite Errors	100	67	17	0	8	8

[1]Lineage classes: FT – Forest Throughout, NFT – Non-Forest Throughout, DEF – Deforestation, REG – Regrowth, CYC – Cyclic.

Table 3 Tasmania Lineage information

quite as good as nationally. The Forest definitely wrong error rate is similar at ~3% whereas the definitely incorrect Non-Forest class, is slightly better than the national average (2%). The total percent probably or definitely correct is comparable (87% for Australia and 90% for Tasmania). Results for Regrowth and Deforestation are very different however (up to a third of Regrowth being erroneously classified). It should be noted, however, that this information is derived from a very small sample.

In the method developed, there is no explicit evaluation of the quality of change maps. In effect, one evaluates the classification of a change map for one time period. One is therefore not in a position to say that landcover change has or has not been correctly identified. Instead, one can only reason that, if in Tasmania there is a tendency to identify Forest that is not really there, then there is a possibility that too much Regrowth and/or too little Deforestation has been identified. A tendency to identify Non-Forest for areas that are judged by photo-interpreters to be Forest would lead to the opposite conclusion – it may be that the amount of Deforestation has been overestimated and/or the amount of Regrowth underestimated. This depends, of course, on the nature of the pixels examined. If pixels that have been erroneously identified as Forest remain erroneously classified as Forest over the entire study period, then they will not lead to an overestimation of the amount of Regrowth although the amount of Forest will be overestimated. In contrast, if such pixels were initially classified as Forest and then from some date onward were misclassified as Non-Forest, then the amount of Deforestation will be overestimated.

To evaluate this, the lineage data are employed. To produce Table 3, definite errors have been tabulated by their lineage class. It would also be possible, of course, to tabulate probable errors, definitely correct classifications, etc. For Tasmania, whilst 2% of the total sample points were in the Regrowth lineage class, 8% of definite errors were in this class. This suggests that the incorrect classification of Non-Forest pixels as Forest may be influencing the Regrowth class. Given that the number of definite errors is small (12), this might be ignored. However, the previous table for Tasmania (Table 2) indicated a potential problem in probable errors. Hence, it might be more useful in the case of Tasmania to also tabulate probable errors by lineage class – a relatively simple undertaking.

Figure 2 Graph showing Definite Errors vs. Quantum of Change

Using the two types of tables presented and interpreting them in tandem identifies areas of potential problems, even though a definitive statement of Correct/Incorrect classification is not presented, and interpretation of the tables requires a knowledgeable user. The methodology cannot be employed, however, without consideration of a number of issues.

One issue is the sampling scheme employed for both aerial photo selection and individual sample points on each image. Photos were selected for use based on their geographic and ecological distribution. However, no attempt was made *a priori* to obtain either a completely representative sample or a completely random sample. Therefore, it is not appropriate to say, for example, that the amount of Forest has been overestimated across all of Tasmania. While there is no known sampling bias related to photo selection, the sampling scheme employed is probably not statistically robust enough to make reliable inferences for all of Tasmania. This is not a problem, however, if one limits the interpretation of results to their original purpose – to identify any potential problems in classification to improve the change map methodology. As for the point samples on the photographs, points were randomly selected from the grid that was overlayed on a photograph. However, because the same grid was employed regardless of photo scale and landscape conditions, the effects of spatial autocorrelation were probably present in the sample points extracted from a single photograph and this effect would vary from photo to photo. For example, for a standard size (23 cm by 23 cm) 1:20000 photograph, grid points are spaced approximately 115 m (ground distance) apart whereas on a 1:80000 photograph they are spaced 460 m apart. In the method developed, no control was placed on the geographic distribution of points selected from a single photograph, nor was any attempt made to quantify the effects of spatial autocorrelation. It remains, nonetheless, that 1:80000 photographs were probably more representative of general landscape conditions than 1:20000 photographs that cover a smaller area.

3.2 Prioritisation

It is useful to consider the confirmed errors, in deforestation and regrowth, for each map tile against the quantum of change. It is possible to then determine the "performance" in error rate against the "importance" in the quantum of change.
The error rate is taken as the average percentage definitely wrong for the Forest and Non-Forest classification. The quantum of change is the scaled sum of deforestation and regrowth reported in Jones *et al*., (2004). Figure 2 plots each mapsheet definite error rate against its corresponding quantum of change. Decision lines are then used to divide the graph into four regions: High Error / Low Change -Medium Update

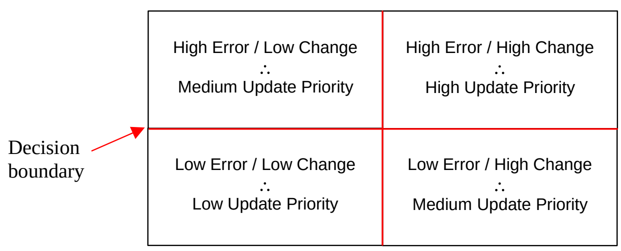

Figure 3 Explanation of update priority graph

Priority; High Error / High Change -High Update Priority; Low Error / Low Change -Low Update Priority; Low Error / High Change -Medium Update Priority (Figure 3). The decision boundaries were initially set to 20% definite errors and 50,000 ha (20% of the highest change rate). Using these thresholds it is recommended that mapsheets SI50 and SG56 are updated as a matter of high priority; a further seven mapsheets (SD52, SI53, SH56, SH55, SH50, SF55 and SG55) should be updated with a medium priority. The remaining 27 mapsheets performed well in the error rate versus quantum of change analysis and have a low update priority.

4. CONCLUSIONS

The fuzzy evaluation methodology presented here was developed as a useful means for determining if there are problems inherent in the land cover change maps for multiple periods produced from satellite imagery, and in the classification methodology used to produce them. Although the fuzzy nature of the information produced does not provide a readily understood means of determining the accuracy/inaccuracy of a land cover change map, we believe that having information that forces an analyst to examine a variety of aspects of classification accuracy is a positive aspect of the methodology because it forces a map consumer to take responsibility for the ultimate use to which the map information is put. The qualitative statements made by photo-interpreters regarding general observations about photographic quality or the general misclassification of an area covered by an aerial photograph are also instructive for subsequent improvement cycles. The combination of textual and statistical (tabulated) information provides for continuous improvement in addition to static reliability statements.

The continuous improvement approach executed in this program aims to do more than just verify the reliability of the NCAS mapping. Continuous improvement responds to the ongoing development and updating of the NCAS land cover program by looking at the source and significance of potential errors. This allows for a targeted and prioritised rectification of any problems that can be assessed and, if necessary, further amended on each round of updating and continuous improvement.

Further work:
The most recent verification period (2000-2002) employed IKONOS imagery as the high-spatial resolution reference data. The effect of this new dataset and inter-comparison to the aerial photographic archive has not been quantified.

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