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Video Strip Mapping (VSM) and Patch Dynamics Analysis for Revegetation Monitoring of a Pipeline Route

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송유관선로의 식생복원 감시를 위한 비디오선형지도화 및 patch dynamics 분석

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Abstract : This paper reports that a new remote sensing technique focused on a narrow and long strip target (e.g. 15m wide and 100km long) has been specifically developed for pipeline ROW (Right-Of-Way) recovery monitoring. With video it was possible to isolate the major vegetation communities of the narrow pipeline ROW with acceptable spatial precision by visual or quantitative methods. It was particularly useful when used to assess a variety of spatial patch dynamics for ROW recovery through digital change-detection techniques in a GIS environment. The main conclusion of this paper is that VSM is a realistic operational technique for a pipeline ROW application. The results also indicate that VSM could be extensively used for other examples of linear thematic mapping.

Key Words : video strip mapping, patch dynamics analysis

요약 : 본 논문은 좁은 폭이지만 장거리에 걸쳐있는 지상목적물 (15m 폭에 400㎞길이)에 대한 새로운 원격탐사 및 GIS기법의 개발을 보고한다 (송유관건설로 파괴된 식생의 복원실태를 모니터링하고자). 비디오는 visual 또는 quantitative해석방식에서 신뢰할만한 정확도를 가지고 복원된 주요식생군락을 분별해냈다. 또한 GIS환경에서 digital change-detection 기법을 통해 복원된 식생의 공간적인 patch dynamics의 분포실태를 평가하는 도구로서 비디오가 아주 유용하게 사용될 수 있음을 보여주었다. 본 연구의 결론은 비디오선형지도화가 송유관선로의 환경감시를 위해 현실운용이 가능한 기술이다는 것이며, 여타의 선형목적물에 대한 환경감시를 위해서도 효율적으로 사용될 수 있음을 보여준다.

1. Introduction

During the two decades following World War II, remote sensing centred on the acquisition and use of many types and formats of vertical aerial photography. The early 1970s saw the advent of airborne and satellite-borne non-photographic sensors. Environmental managers were given a more synoptic view from space than was ever available from aerial photography. In this context, over the last 20 years, the majority of remote sensing research has been used to support global, national, or large area applications (Um, 1992). As a consequence, those charged with more site specific responsibilities, such as the environmental monitoring of a linear development facility, have benefited far less from the fruits of that research.

Environmental monitoring on sites disturbed due to the construction of power plant, transmission lines, gas lines, utility roads and other related linear facilities is essential as it is required by regulatory agencies (Chan, 1984; Flach et al., 1989; Farrington et al., 1993). Utility companies are actively involved in monitoring natural landscape areas which have been disturbed by such linear developments. Environmental monitoring for

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corridor-based facilities is different from the traditional targets of area-based mapping. The corridor itself is linear and generally very long (hundreds or thousands of kilometres) and very narrow (10-100 metres). The type of facility which fits these criteria include cross country pipelines, electric transmission lines and overhead cables, but also include railways, roads, highways, rivers and coastlines. Railways, transmission lines, pipelines and fibre optic cables are physically quite dissimilar. All of these facilities do, however, fit the description of corridor target for purposes of environmental monitoring. Such corridor-based facilities have a number of characteristics in common: the facility is expensive to build, expensive to maintain and is subject to strict environmental regulation.

However, very few research has been made to identify an appropriate remote sensing/GIS technique for linear thematic mapping. In this regard, a recent research set out to evaluate the operational potential of VSM for ROW site monitoring (Um and Wright, 1996; Um, 1997a and b; Um and Wright, 1998a). Also, this study particularly investigated whether large-scale changes in ROW could be monitored, permitting annual survey results to be updated on a site-specific basis. Initially, some essential background related to video strip mapping is explained. The following discussion introduces the study site and the data used. There are several different approaches for digital change-detection study (Milne, 1988). For this study, standard digital image processing has been applied. Firstly, two data sets (1989 and 1995 video) were co-registered geometrically and radiometrically. To eliminate undisturbed sites from the change-detection study, a spatial mask for the area was created by digitizing the ROW coverage alone, for the entire image. Each image was then classified separately. The result of the classification was analysed in a GIS environment to identify the patch dynamics of vegetation recovery in the ROW. To demonstrate the usefulness of patch dynamics analysis, further discussion evaluates the recovery status based on the result of the dynamics analysis.

2. The Value of Video in a Corridor Application

For the requirements of corridor monitoring, various sensors can be deployed from satellite or aircraft, (from photographic cameras to scanners and complex imaging spectrometers). Satellite image resolution is still limited to a minimum mapping unit of 10m per pixel. This is too coarse a resolution for monitoring pipeline corridors as narrow as 15m. It is still necessary to use aerial photography to get specific fine details at the larger scales.

The cost of inventory mapping with aerial photography would be a good standard against which a video sensor could be readily compared. To monitor the 400km length of pipeline with aerial photography of 100m swath, the number of photographs required is estimated at 10,000 frames (as shown below[1)]). The cost would be increased several times for multi-year monitoring. It is, therefore, considered too expensive to monitor a long narrow pipeline frequently by aerial photography. Due to such limitations, ROW site monitoring using aerial photography has not achieved operational status, although a few previous attempts have been reported (Hoover, 1974; Aird, 1980; Ellis et al., 1984; Jadkowski et al., 1994).

With airborne video, dynamic stereo coverage is achieved in each single flight line by recording a very large number of individual frames within a very short time interval. Thousands of aerial photographs would be required to provide the same stereo coverage as recorded on one hour of video tape. With airborne video, the linear extent of hundreds kilometres of a pipeline can be recorded all on the same day. Additionally, videography is much less expensive than most other remote sensing systems (Wright, 1993). Due to such low-cost data acquisition, this technology may have a particular value in highly changeable areas, such as the revegetating corridor of a pipeline ROW, where year-to-year and seasonal changes are common.

Another important element in remote sensing applications is the required optimal swath width. Field of View (FOV) differences provided by various remote sensing sensors will find application at different scales. Sensor sizes in solid-state video cameras are usually much smaller than the formats of conventional photographic film (36mm by 24mm for small format, 55mm by 55mm for medium format photography) as shown in Figure 1. The view-angle of the imaging device must first be carefully considered when trying to obtain remotely sensed data of a long, narrow target. Wide-angle imagery, such as from airborne line scanner and photography, generally covers a larger area of land surface than a smaller format system operated at the same altitude and with the same focal length lens.

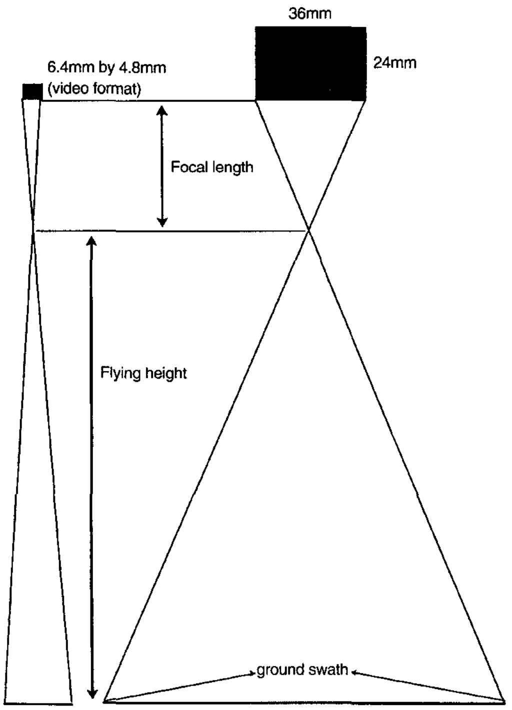

Figure 1. The relationship in ground coverage between video sensor and photographic film (small format) at the same altitude and with the same focal lens.

To fulfil the data requirements of corridor monitoring it is sufficient to have information along a swath in the immediate vicinity of the corridor disturbed. There is much recording of redundant information in linear applications using traditional area-based sensors. Furthermore, if large areas are to be covered to detect sufficient ground detail, the cost disadvantage will apply to the whole coverage. Corridor monitoring represents a potential application for remote sensing which is largely unfulfilled. Aerial video is a technology that fills a niche that conventional aerial photographs cannot meet.

3. Data and Study Site

A problem associated with using historical remotely sensed data for change-detection is that the data are usually of non-anniversary dates, with variations in sun angle and in atmospheric and ground moisture conditions. This study proved to be no exception, with all of the above problems being encountered. Vertical VHS (Video Home System) video imagery had been acquired at the time of the pipeline route survey in 1989 over the study site, which is part of Shell North West Ethylene Pipeline (NWEP) in the UK. The video had been taken for the entire 400km pipeline length of NWEP by helicopter, using a VHS camera at 150m altitude with widest angle-of-view of the camera (10.5mm focal lens setting). The archived 1989 video imagery was used for this change-detection study. In 1995, near-vertical S-VHS (Super format, giving 420 rather than 230

Table 1. Detailed specifications of video imagery used for revegetation monitoring

	1989	1995
Date	Early April	15:00h, 5 August
Altitude/focal length	150m (500 feet)/10.5mm	300m (1000ft)/15mm
Swath (along track-coverage)	8.8mm(sensor size) [150/0.0105] * 8.8= 125.71m	6.4mm(sensor size) 128m
Platform	Helicopter	Cessna 172

horizontal lines on display) video imagery was acquired over the study site, to detect ROW recovery after the pipeline construction. Details of the data are given in Table 1.

Based on data availability, the Armadale moor section was selected as a study site. This section covers 0.5km of pipeline and is located between Glasgow and Edinburgh (Scotland, UK), near to the village of Armadale (Ordnance Survey, O.S. Grid Reference: 291219.19E, 667186.79N). The topography of the site is generally flat. Most of the soil is peaty and acidic, and on a raised bog the soil is particularly waterlogged (Shell Chemicals UK Ltd., 1992). During the project, the experiment was mainly carried out in the northern part of the experimental site (ground coverage: around 300m long, Community A B C and Transect T 1, 2, 3 in Fig. 2). This size of ground target was considered appropriate and manageable for methodology development, since intensive investigation over small areas can provide a valid assessment of the performance of video in a change-detection application (RSK Environment Ltd., 1995).

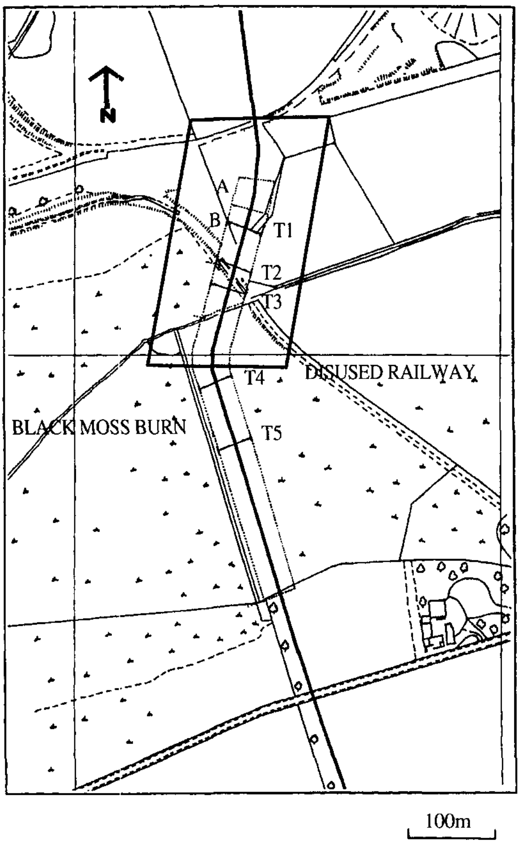

Figure 2. The location map of the study site, The video coverage is marked as a polygon.

4. Interpretation of the Multi-temporal Images

Standard image pre-processing was applied throughout the image registration procedure. After the pre-processing, only a portion of the video has been interpreted since it was expected that intensive investigation of only the ROW portion in the video would provide a clear illustration of the potential of video in change-detection study(Um and Wright, 1998b). The image interpretation has, therefore, just concentrated on the coverage of the area disturbed by pipeline construction (within the pipeline boundary fence), which is marked as a polygon in Figure 3B and presented in Figure 4[2].

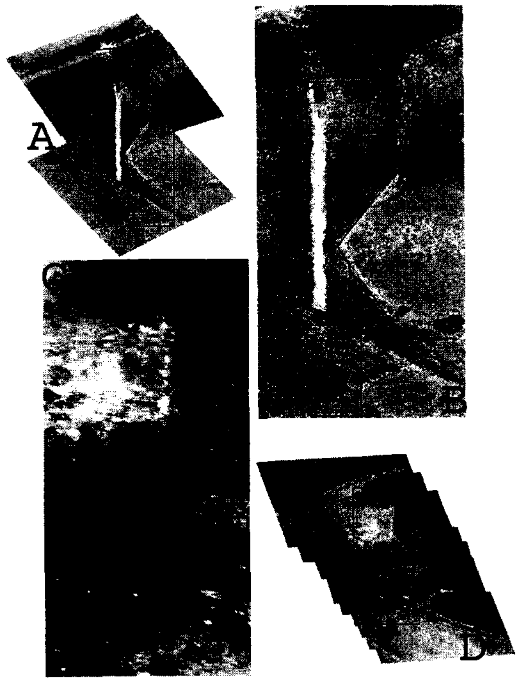

Figure 3. The video images used for revegetation monitoring, A: 1995 video, (rectangle: coverage of right magnified video), B: magnified portion of 1995 video (polygon: the area assumed to be disturbed by pipeline construction), C: magnified portion of 1989 video, D: 1989 video.

Consequently, the partial subscene covered around a 15m swath width. These partial images have been used for the remainder of the entire experiment in this project for the discrimination of ROW recovery.

1) Visual Interpretation

The summary of the visual interpretation is presented in Table 2. In the 1989 video, many ground features tended to blend into each other, indicating the strong influence of the poorer spatial resolution of the VHS system and lower signal-to-noise ratio. For example, heather patches in the 1989 video are confused with grass in terms of colour intensity, while they are clearly separated in the 1995 video.

Legend
M : moss
P : wet peat
S : bare soil
B : broom
H : heather
G : grass
W : waterlogged area

Figure 4. The result of visual interpretation A: 1989 video, B: 1995 video

Nevertheless, the basic ground features of the moorland sites were at least distinguishable in the 1989 video images. The marked seasonal difference in the appearance of moorland from the 1995 video is recognizable in the 1989 image.

The 1989 video had been recorded at the end of the wet season, in April 1989, when the ground vegetation had just started to grow. These climatic conditions are portrayed in the video images as colour differences compared with the 1995 summer video. Four grey tones are present in the 1989 image (corresponding to moss, heather, wet peat and grass). Moss fields were the dominant ground cover in the study site in 1989. The presence of increased moisture in the wet season was the main

Table 2. Summary of visual interpretation of the multi-temporal video images

Ground classes	1989	1995
Grass (G)*	medium light-green to dark-green	mottled green/whitish yellow/light-green
Wet peat (P: 1989) /waterlogged area (W: 1995)	dark-brown	dark-brown
Heather (H)	light-brown	brown/reddish-brown
Moss (M)	bright-yellow	NA
Broom (B)	NA (Not Applicable)	green
Bare soil and stones (S)	NA	whitish-yellow

* Letter codes are marked in the multi-temporal video images in Figure 4.

factor contributing to the moss species present. This cover type was distinguished by a bright yellow smooth texture at the northern end of the study area (Fig. 4A). There appeared to be considerable coverage of wet peat, which shows as a dark brown colour. Heathers were located in the eastern part of the present ROW area along the pipeline trench. They are distinguished by light brown against the surrounding peat soil area. The grasses were identifiable as ranging from medium light-green to dark-green, with coarse texture.

In the S-VHS image of 1995, the visual separation of vegetation cover types is generally very good, and resembles an aerial photograph (Fig. 4B). The shapes and sizes of vegetation blocks are accurately delimited and small-scale differences are well resolved in this video. For example, rush patches scattered in the entire image are represented by mottled tones. Grass and heather classes can evidently be identified by two different levels of sparse and dense cover with distinct tones. In the 1995 video, even four years after pipeline construction, at all sites the vegetation conditions in the ROW easement area were considerably different from those on the undisturbed moorland. One of the most common problems arising from pipeline construction is due to compaction by the heavy vehicles used to dig the trench and lay the pipe. Compaction can irreversibly damage soil structure and cause waterlogging and drainage disruption. Initial observation of the video clearly disclosed severe soil disturbance and rutting along the right of way, as shown in Figure 4B.

2) Computer-assisted classification

Basically, the thematic ground classes identifiable by visual interpretation were used as individual classes in a computer-assisted classification (these classes had also been identified by RSK Environment, Ltd., as key indicators of vegetation recovery status in the pipeline corridor). However, to minimise misclassification (caused by inherent limitations of machine-based analysis), the number of thematic classes has been selected within the range of visually distinctive grey levels in the image. Training samples for four classes were selected in the 1989 video: moss, heather, grass and wet peat, while five ground features classes were sampled in the 1995 video: heather, broom, bare soil, grass and waterlogged area.

Training samples were used in a maximum likelihood classification and classification maps were generated (Fig. 5A and 5B). Visual inspection showed that the results of classification generally corresponded to the visual interpretation of the image. The two dates of video distinguished roughly the overall ground features, which was impossible with the field data alone. However, the waterlogged area in the 1995 video has been confused with the adjacent heather class. There was also a little

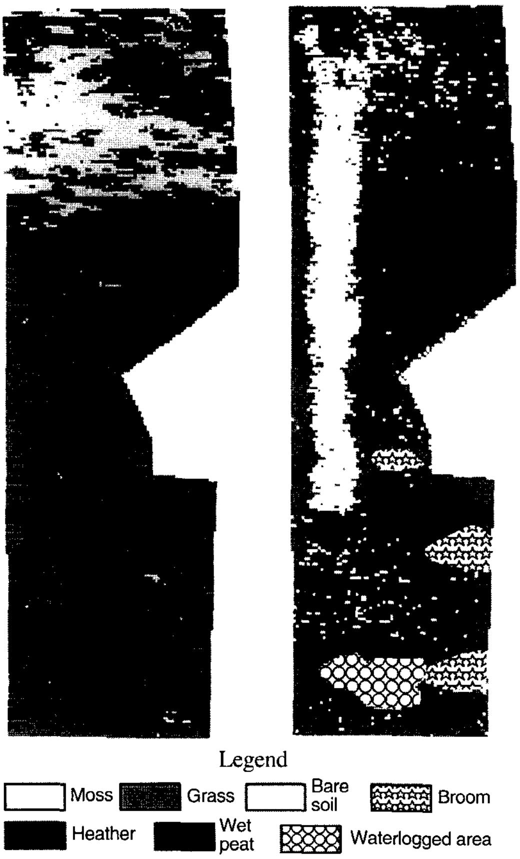

Figure 5. The result of computer-assisted classification, A: 1989 video, B: 1995 video

confusion between grass and broom. Thus, these classes have been manually reclassified by screen digitizing of polygons as shown in Fig. 5B.

Table 3. The results of multi-temporal video classification

1989	percentage	1995	percentage
Heather	28.89	Heather	18.35
Wet peat	25.29	Bare soil	16.53
Grass	32.53	Grass	59.00
Moss	13.28	Broom	3.22
		Waterlogged area	2.90
Overall biomass content	74.7		80.6

Areal estimates are presented in Table 3. The greatest increase is noticed in the grass cover (32.53% to 59%). This apparent increase was attributed to the dispersal of sown grass after pipeline construction. Overall biomass content is estimated by excluding non-vegetation classes: e.g. bare soil (16.53% in 1995), waterlogged area (2.9% in 1995) and wet peat (25.29% in 1989) in the entire ground cover. It is noted that overall biomass content had increased during 1989-1995 (74.7% to 80.6%). It seems that this is due to intensive seeding of grass species. It was initially expected that a considerable loss of heather would be detected, caused by the access road and creation of drainage disturbance. On the contrary, the result shows that spatial occupation by heather has only dropped from 28.89% to 18.35%, between 1989 and 1995, which reveals that the heather loss was not serious at the site[3)].

5. Analysis of patch dynamics

The classification results by strip video present a snapshot in time of vegetation recovery. Ecosystems in ROW site recovery are quite dynamic and cannot be adequately described by isolated comparisons of classification results of the remotely sensed data. The integration of GIS and remote sensing (RS) permits an understanding of the correlation among the information generated from the RS classification. To identify important baseline information in assessing problems in the disturbed site and suggesting possible countermeasures, it would be desirable to understand the dynamics of the revegetation process in pipeline ROW. Also, spatial association of these recovered ground features can be expected to provide an identification of features affected by engineering work during the construction phase, and post-management at the operational phase. Several research studies have already been conducted to derive patch dynamics of ecosystems in a GIS environment (Qi, et al., 1992; Ulliman, 1992; Hulshoff, 1995). The types of ecological impact

< biomass content dynamics>

- devegetation
- non-vegetation
- revegetation
- primary vegetation cover (PVC)

< Native species recovery dynamics>

- native moorland associated species loss (NMSL)
- habitat condition change (HCC)
- recolonized heather
- native heather recovery (NHR)
- weed dispersal
- native weed recovery (NWR)

which might be addressed in this way include: direct habitat loss, habitat modification, habitat fragmentation (reduced size of remaining habitat), and movement of primary vegetation cover.

Measurement results obtained from multi-temporal monitoring by remote sensing were used to assess a variety of spatial and temporal characteristics of ROW site recovery. In accordance with user requirements, the results of the classification of video data can be manipulated to produce patch dynamics in a diverse pattern. Such excessive losses of soil, nutrients and seeds from the ecosystem during pipeline construction affect the regeneration capacity of the vegetation, and thus causes irreversible environmental damage. The basic requirement of ROW recovery would be to achieve compatibility between disturbed and undisturbed sites. This could be evaluated by investigating the changing dynamics of overall biomass content, before and after pipeline construction.

Another goal for vegetative recovery of such disturbed areas is the re-establishment of the species composition and habitat condition that existed prior to disturbance. This would be a main concern of the environmentalist and ecologist. It was decided that this study would evaluate changing trends for overall biomass content on the ground, and native (primary) landscape changing patterns before and after disturbance, since these are regarded as basic indicators in understanding environmental disturbance caused by pipeline construction. To derive reasonable criteria for co-relationships between 1989-95 ground classes, ground truth information and existing prior knowledge were incorporated.

Patch dynamics analysis can be explained through a matrix analysis procedure in the image processing/GIS package, Erdas 7.5. For analysis of biomass content dynamics, if the grass in 1989 is classified as bare soil or waterlogged in 1995, then it is recorded as devegetation. Meanwhile, if wet peat without vegetation cover in 1989 is classified as heather in 1995, then this is recorded as revegetation. On the other hand, for native species recovery dynamics, if a heather covered area in 1989 is classified as heather in the image in 1995, then this area is recorded as native heather recovery (NHR). If a moss area in 1989 is classified as bare soil or waterlogged area in 1995, then this area is recorded as native moorland species loss (NMSL) in 1989-95. Where the wet peat in 1989 is changed to a grass patch, it is recorded as seed dispersal. This is the basis of GIS modelling from a video remote sensing classification. Using this information, a matrix was generated (Tab. 4). In a GIS environment, various types of mapped output for patch dynamics were produced, as shown in Figure 6A and 6B. This output shows redefined ground features as follows:

Table 4 shows statistics acquired from the matrix analysis in a GIS environment. 15.67% of the ground cover has undergone devegetation between 1989 and 1995 and the devegetated area is now covered by bare soil and waterlogged area caused by the pipeline construction. A considerable area of ground cover has also been revegetated over moss and wet peat areas in 1989 after pipeline

Table 4. Matrix of patch dynamics analysis

1995 1989	Bare soil/waterlogged area	Heather	weed (grass, broom)
Moss	NMSL/ devegetation	recolonized heather/ revegetation	weed dispersal/revegetation
Heather	NMSL/ devegetation	NHR/PVC	weed dispersal/ PVC
Wet peat	HCC/ non-vegetation	recolonized heather/revegetation	weed dispersal/revegetation
Grass	NMSL/ devegetation	recolonized heather/ PVC	NWR/ PVC

construction and, currently, there is recently colonized vegetation of 31.01%. Primary vegetation cover during 1989-95 comprises 49.55% of the total ground cover. In general, the entire biomass content is not low. However, with this data, it is difficult to determine such factors as low production by natives due to competition from seeded grasses, physical inhibition of germination by bare soil and waterlogged area. There are insufficient data to explain in detail the patch dynamics of how the native landscape condition (before disturbance) has been recovered. It is likely that they are the combined result of post-construction site management and natural ground conditions.

This study attempted to analyse the recovery of native ground conditions in conjunction with present ground conditions. In general, colonisation by moorland plants was restricted due to the vigorous initial growth of sown grasses and invading broom (42.48%). For native grass species, it is noted that the native weed recovery (19.72% in Tab. 5) is much less than the grass cover of 1989 (32.53%, see Tab. 3) considering the ground disturbance by pipeline construction. Heather (Calluna Vulgaris) had started to colonize the grass sward with a percent cover value of 14.94%, whilst native heather recovery was recorded as 3.42%, which depends on the turfing method at the time of pipeline construction. As in the case of biomass dynamics, the bare soil and waterlogged areas have contributed considerably to the entire present ground cover. Native moss, heather and grass have

Legend

<Biomass content analysis>

■ Devegetation

□ Non-vegetation

■ Primary vegetation Cover (PVC)

▒ Revegetation

<Native species recovery analysis>

□ Native Moorland associated Species Loss (NMSL)

Habitat Condition change (HCC)

▒ Recolonized heather

■ Native Heather Recovery (NHR)

■ Weed dispersal

■ Native Weed Recovery (NWR)

Figure 6. Patch dynamics analysis maps

Table 5. Results of patch dynamics analysis

biomass content dynamics	percentage	native species recovery dynamics	percentage
devegetation	15.67 %	native moorland associated species loss(NMSL)	15.67 %
non-vegetation	3.77 %	habitat condition change (HCC)	3.77 %
revegetation	31.01 %	recolonized heather	14.94 %
primary vegetation cover(PVC)	49.55 %	native heather recovery (NHR)	3.42 %
		weed dispersal	42.48 %
		native weed recovery (NWR)	19.72 %

been replaced as a value of 15.67% in total ground cover by bare soil and waterlogged area (NMSL) which is the same criterion as the devegetation class of biomass dynamics. It is reinterpreted as native moorland species loss (NMSL) in the interest of native species preservation. Wet peat (25.29% in 1989, see Tab. 3) has been lost as a 3.77% (HCC) by the same disturbance (bare soil and waterlogging). It was evaluated as just non-vegetation during 1989-1995 in the previous biomass analysis. This is assessed here as habitat condition change (HCC) in consideration of native ground condition disturbance.

The biomass patch dynamics indicate that the disturbed ROW goes positively on a trend toward recovery, since current biomass content on the ground is considerably higher (80.56%: revegetation – primary vegetation cover = overall biomass content of 1995 video classification) than that of 1989 (74.7%). However, the results (e.g. native heather recovery: 3.42%) show that the re-establishment of the original vegetation and habitat condition is taking place slowly and attribute this to be largely the result of poor mixing of sub-soil and top-soil during construction, combined with poor site management after construction. Such overall patch dynamics for vegetation recovery cannot be analysed from the field ecological survey but was successfully demonstrated here. In addition, the procedure will be more appropriate when broad overview classes (e.g. areas of change and no-change are being differentiated, after the spatial distributions of different ground features in the sequential images have been identified.

6. Conclusions

This study has demonstrated that change-detection using video can be completed for factual assessment of pipeline corridor recovery, overcoming the limitations of field survey practices. The video acquired for the initial pipeline project design provided a permanent record of the landscape against which later changes could be compared (basic information about the amount of vegetated area at the time of the earlier 1989 video). Recent video was also a considerable positive tool to provide spatial knowledge for the reinstated ROW site. The results of such visual and statistical classification of video provided a good basis for general understanding of the potential of video in a change-detection study: the appropriate interpretation techniques and likely levels of accuracy. Patch dynamics analysis was shown to be a powerful tool for quantifying areal extent and analysing ROW site recovery trends along a narrow corridor. The main conclusion of this project is that VSM is a realistic operational technique for monitoring vegetation recovery of a pipeline ROW corridor.

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Notes

1) Estimation of number of photos required for 60% stereo overlap.
Estimation of along-track ground coverage = (along-track format size of small format photographic camera: 36mm) * flying height (300m)/focal length (106mm) = 100 m
Net gain = along-track ground coverage (100 m) * 4/10(standard forward overlap 60%) = 40 m
The number of photographs required for stereo-cover = 400km/40m = 10,000 exposures
2) The original colour video and its processing results are here presented in black and white. However the description of video in this paper is based on the original colour video image since its information content and image clarity are even better than that in black and white.
3) To carry out a reliable comparison between the multi-temporal videos, an objective accuracy assessment for the statistical classification was necessary. However, there are many limitations to introduce such a procedure into the centimetre pixel size applications of this project (reliability of the reference data, mis-registration in time etc). The performance of video has, therefore, been evaluated based on the result of the visual interpretation (which is based on ground truth and field survey).

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