FEASIBILITY TO DETECT SIGNS OF POTENTIAL CO_2 LEAKAGE WITH MULTI-TEMPORAL SPOT SATELLITE VEGETATION IMAGERY IN OTWAY, VICTORIA

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ABSTRACT:

This paper presents image processing results for the OtwayCO2storage site, a demonstration project of CO_2 sequestration in south-western Victoria, Australia. These results were derived from SPOT-VGT S10 datasets of 2001 to mid 2011. Over 65,000 tonnes of CO_2-rich gas stream was injected into a depleted gas reservoir at a depth of 2050 meters at the site since 2008. Over time, CO_2 migration up-dip within the 31m thick reservoir sandstone capped by the impervious thick seal rock has been recorded. But no top soil contamination has been discovered. This study has analysed the site vegetation growth using NDVI as a measure on a pixel by pixel basis. The multi-year time series result shows that NDVI values at the site regularly vary according to the seasons. Furthermore, precipitation levels were fluctuating in the past 10 years, especially in the years of 2002 and 2006, which correlated with low NDVI measuring results. But there are detected hot spots that cannot be linked with rainfall. Authors have found that some hot spots correspond with site well drilling and pipelines construction periods and locations. While others might be due to image data biased. Therefore, certain low NDVI spikes in the temporal evolution results cannot be attributed to only drought or pasture grazing. These subtle changes detected in the NDVI index prove the ability to use satellite image for providing valuable information to decision makers in relation to CO2 sequestration site environmental safety monitoring for searching CO_2 leakage signals.

1. INTRODUCTION

Using underground reservoirs to store CO_2 has been tested globally as an effective technique to reduce greenhouse gas emissions. But in the meantime, the public have raised concerns about the stability of geologic formations to hold large amounts of carbon dioxide for the long term. People worry that CO_2 could migrate or leak into the top soil through geological faults or cracks, fractures of rocks, or an abandoned well connected with the reservoir. The leaked CO_2 gas can displace oxygen from the roots of plants at the surface and thus cause the plants to die. This phenomenon has been discovered from natural CO_2 gas seepage caused by a volcano eruption (USGS, 2000). Also the leaked CO_2 could change the pH and redox of soil and alter natural microbial environments (Noomen et al., 2009). Consequently, over time, vegetation in CO_2 contaminated soil can display characteristics such as stunted growth, reduced water content, or decreased leaf chlorophyll concentrations. Asides from CO_2 gas killing vegetation, it also can lead to asphyxiation in humans and animals at higher concentrations. These problems have driven public concern over the environmental safety of CO_2 sequestration sites. In response, scientists are motivated to develop effective methodologies for confirming the stability and suitability of selected geological formations to store CO_2 and to monitor for any signs of CO_2 leakage. In this paper, the authors have proposed to apply the SPOT-VGT S10 images to indirectly detect the presence of CO_2 by tracking vegetation stress changes through Normalized Difference Vegetation Index (NDVI) analysis in OtwayCO2CRC site. However, the vegetation growth signature value of NDVI from optical image can be impacted by differing factors such as the seasons, weather, precipitation, and human activity. Therefore, the temporal evolution results of NDVI need to be assisted by a trend value derived from regression analysis with multiple years' statistical model.

2. STUDY AREA AND DATA SAT

2.1 Otway CO2CRC site

The CO2CRC Otway storage Project (Figure 1) is the first advanced geosequestration project in Australia and the world's largest research and demonstration project. Work at the Otway site commenced in as early as 2002 (Figure 2). It can be seen that vegetation has been cleared at the construction site and along the route for the pipeline. Since April 2008 about 100,000 tonnes of CO_2 have been injected and stored in a depleted gas reservoir 2km deep underground and further injections into different geological formations are being planned.

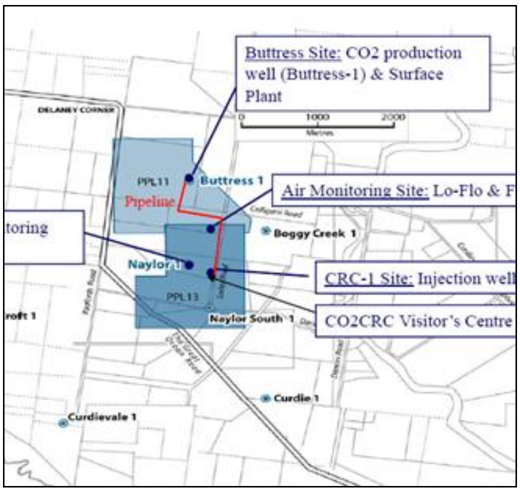

Figure 1. Otway CO2CRC Sequestration project, Victoria, Australia

Figure 2. Execution phase at Otway CO2CRC

2.2 Study dataset

A total of 378 images acquired by the French SPOT© (SPOT Image Copyright 2011, CNES) optical remote sensing satellites between January 2001 and July 2011 over the Otway CCS site have been used to analyse vegetation growth dynamics. This aims to establish a relationship between vegetation stress and possible CO_2 leakage signals. Because NDVI is strongly influenced by precipitation, temperature, and also grazing and farming activities, multi-year NDVI time series have to be used so that each contributor can be identified accurately.

The VGT-sensor registers 1728 pixels in line, with a sub-nadir resolution of 1.15 km and a swath with of about 2200 km. Furthermore, the VGT-sensor simultaneously registers in 4 short wave bands: BLUE, RED, NIR and SWIR. Table 1 gives the specifications of SPOT-VGT. The raw VGT-S10 data are in Plate carrée projection with a 0.0089285714-degree pixel resolution. These multi-temporal data were transformed and re-sampled using a nearest neighbour operator into the UTM projection based on WGS84 spheroid at 1km resolution by using in house automated GEOS-VGTS10-NDVI software.

Table1. Characteristics of SPOT-VGT 4, 5

Satellite	SPOT-VGT 4	SPOT-VGT 5
Altitude	822 km	
Inclination	98.7 degrees	
Orbit	sun-synchronous polar	
Period of revolution	101 minutes	
Swath width	60 x 60 to 80 km	
Repeat cycle	26 days	
Band	B0, B2, B3 and MIR	
Spectral band	0.43 – 0.47μm (blue) 0.61 – 0.68 μm (red) 0.79 – 0.89 μm (near IR) 1.58 – 1.75 μm (mid-IR)	
Period	24/03/1998 – still operational	04/05/2002 – still operational

3. METHODOLOGY

Using NDVI index to determine vegetation condition is based on the fact that healthy vegetation has a low reflectance in RED (visible) electromagnetic spectrum due to plants' chlorophyll absorption, and high reflectance in NIR (near infrared) because of internal reflectance by mesophyll of the green leaves. We calculate the NDVI index using SPOT-VGT S10 image pixel's reflectance values of RED and NIR by equation (1):

$$NDVI = (NIR - RED)/ (NIR + RED) \qquad (1)$$

Where, NIR is near infrared reflectance in band 3
RED is visible light reflectance in band 2

The value of NDVI is limited between +1 and -1. Normally, the NDVI of vegetation will vary between 0 to +1. The value closing to +1 (e.g. 0.8 - 0.9) represents the highest possible density of green leaves. And the value would be close to zero if there are no green leaves. A zero therefore means no vegetation. Besides, the healthy vegetation absorbs most of the visible light and reflects a massive portion of the near-infrared light. And unhealthy vegetation will reflect more in visible light and less in near-infrared.

3.1 Image processing flowchart with GEOS-VGTS10-NDVI

The commercial-off-the-shelf remote sensing software packages such as ENVI calculate NDVI on a patch by patch basis for selected interested area. The output result of this area is the average NDVI of multiple pixels. Hence any change in less than 1km² scale because CO_2 leakage will be smoothed out. Also the result can only be done manually one image at a time. It will take too long to process hundreds of satellite images. In order to derive NDVI time series for areas around the CCS sites on a pixel by pixel basis in a reasonable range, an automated software tool GEOS-VGTS10-NDVI has been developed NDVI time series of 25 pixels or more for areas around the Otway CCS site according to the each pixels location have been extracted from the 378 SPOT images. Figure 3 is the flowchart for processing the VGT-S10 images.

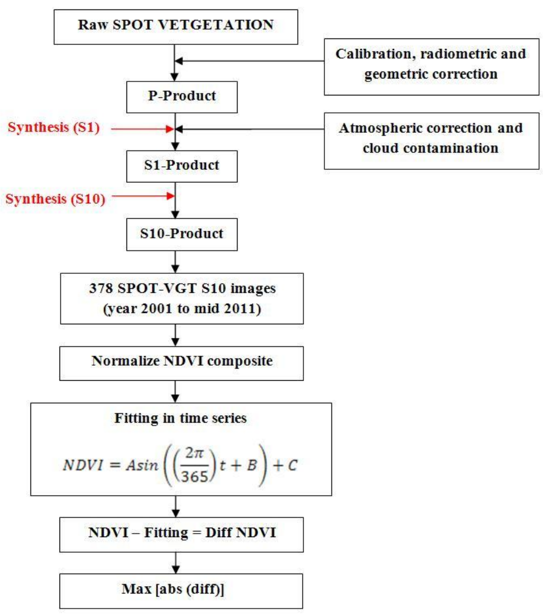

Figure 3. Processing flowchart

3.2 Vegetation cover localized NDVI signature analysis using GEOS-VGTS10-NDVI

In order to track possible CO_2 leakage around the CO_2 injection and storage site, a patch of 5 by 5 pixels has been selected in the SPOT image covering 5km by 5km centred at the CO_2 injection well (Figure 4). The sub image thus contains a total of 25 pixels with 1km resolution. In Figure 5 each pixel has been numbered. The yellow boundary represents the extent of CO2CRC activity areas for drilling and construction. The yellow pin is the location of injection well which is right on the boundary between pixels 13 and 18.

Figure 4. The 25 pixels around the Otway CCS site (selected based on the coordinates of the injection well; latitude: -38.51786, longitude: 142.82143)

4. RESULT AND DISCUSSION

A total of 378 SPOT VGT-S10 images are processed for vegatation growth analysis at this ccs site. The temporal evlution of NDVI value in the past 10.5 years for each pixels are given by figures of 5 and 6. Figure 5 gives the time series result in 2D . It can be seen a clear seasonal sin wave change of NDVI in figure 5, and also with many sharp spikes indecating large amount of NDVI drop.

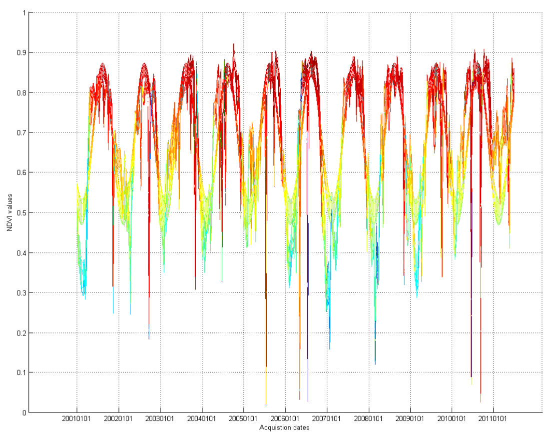

Figure 5. NDVI time-series in 2D for Otway CO2CRC during 2001-2011

Figure 6 is the 3D plot (rotated from figure 5) showing all 25 cells' vegetation NVDI value at the site. Red and Blue colours are for High and Low NDVI values respectively.

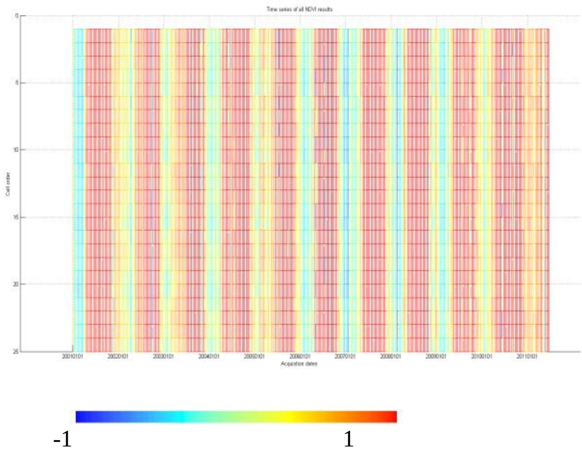

Figure 6. NDVI time-series in 3D

Through least squares fitting of the time series data, a model for the seasonal trend can be obtained as:

$$NDVI = A\sin\left(\left(\frac{2\pi}{365}\right)t + B\right) + C$$

By consider each individual cell is with its own soil condition, although the site is formed by dairy farms only. The fitting coefficients of A, B, and C for all the 25 pixels are specific signatures to each pixel. Thus, the values are slightly varied in between each cell. After subtracting the modelled seasonal effects from each pixel's time series data, the residual NDVI values for all the 25 pixels are plotted in Figure 7-A and 7-B . The residual NDVI values are now mostly between ±0.2. Figure 7-B is 3D version of Figure 7-A. For those residual values below -0.2, we have to consider the causes.

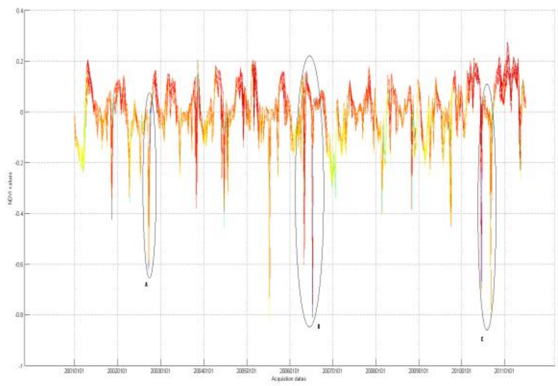

Figure 7-A. Seasonal variations removed 2D NDVI time series.

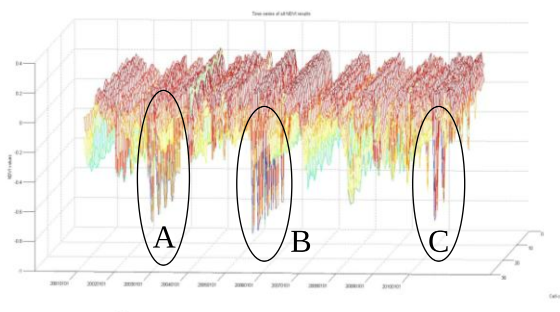

Figure 7-B. Seasonal variations removed 3D NDVI time series.

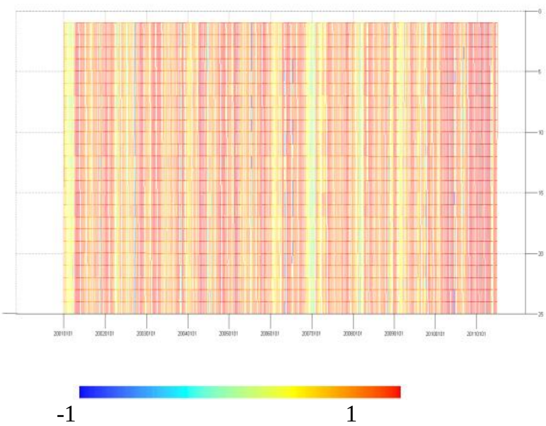

Figure 8. Seasonal variation removed NDVI time series in 3D.

Close attention should be paid to these unusually low NDVI peaks with values below -0.6 in blue colour, circulated as A, B, and C in the figure 7-A and 7-B. Peak A is in later 2002, B mid 2006, and C around mid 2010. The mid 2005 also shows low value. A, B, and C are corresponding to blue colour lines in figure 8 located in cell order and imaging time. In addition, the causes behind the NDVI spikes of unusually low value in Figure 7-A and 7-B could be analysis from the history of well drilling and pipeline construction activities in the Otway CCS site:

- 2002: the Buttress-1 Well was drilled and when it was found rich in CO_2 it was decommissioned.
- 2006: production well tests were carried out in June.
- 2007: drilling of the new injection well to inject CO_2 into the depleted gas field, the Waarre C Formation began on 15 February 2007 and was completed within budget on 15 March 2007. Located 309m southeast from the Naylor-1 well.
- 2007: an integrated bottom-hole geochemical and geophysical assembly was lowered into the Naylor-1 well in a “work over completion” operation from 25 September – 7 October 2007.
- 2207-2008: the pipeline was installed between December 2007 and January 2008. It is 2.25km long, stainless steel and 50mm in diameter.
- 2010: Drilling of a second injection well at the CO2CRC Otway Project in Victoria’s south-west has begun on 1st February 2010, signaling the start of an important new phase of research in Australia into geological storage of carbon dioxide (CO_2)

Year 2002 was a year of lower rainfall less than the average; rainfall in 2005 was almost the same as in 2003; but 2006 was the dries year according to climate data from the Bureau of Metrology (BOM) as given in Figure 9. The red circle represents the period covered by the SPOT imagery used in this analysis. It is important to note that rainfall in 2010 was well above average. Therefore, the extremely low NDVI spikes in Figure 7-A and 7-B cannot be attributed to drought only, although the vegetation growth in the year 2002 and 2006 were affected by rainfall. Overall, all spikes return to normal trend by next one or two image update time. There is no long lasting low NDVI discovered in the site. Therefore, the vegetation cover growth vibration is not caused by CO_2 contamination. There is no sign of CO_2 leaking.

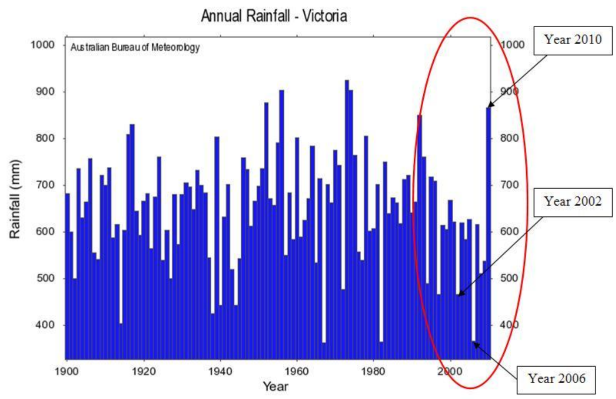

Figure 9. Annual rainfall in Victoria in the last 100 years (BOM, 2011)

5. DISCUSSION AND CONCLUDING REMARK

In conclusion, vegetation stress/ decrease in Otway CO2CRC sequestration site in some periods such as year 2002, 2005 and 2010, was detected through the NDVI analysis on SPOT imagery collected over the past 10.5 years. Those spikes in the residual NDVI time series in Figure 7-A and 7-B (particularly the one in 2006) are possibly caused by the site constructions at few different locations. The areas corresponding to the spikes locate in the yellow line zone for the well drilling site labelled in Figure 4. Researchers’ foot traffic and monitoring facilities’ construction did damage the surface vegetation cover around the site (Figure 2). The maximum NDVI difference from regression model was about -0.8. It can also be concluded that the climate has no significant influence to vegetation over the sequestration site, particularly in 2002 and 2006 although their rainfall is well below average. But relatively low NDVI duration in these two years does longer than other years, which can be observed in figure 5 and 8 for the NDVI value appeared in yellow/green colour, although there are very good irrigation systems around the site. The subtle changes detected from our NDVI analysis in Otway proves the feasibility of the proposed methodology on providing valuable information to decision makers in relation to CO_2 sequestration site safety and environmental management regulations.

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