Ross Morrison

NDVI Vegetation Analysis using UAV Imagery

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University of Jyväskylä

Faculty of Information Technology

Author: Ross Morrison

Contact information: romamorr@student.jyu.fi

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Abstract: Vegetation Indices are used to enhance targeted properties of vegetation. Using algorithms such as the Normalized Difference Vegetation Index (NDVI), the health or stress of green vegetation can be accurately and consistently measured. This literature review looks into the origins of NDVI and the use of UAV's equipped with multispectral sensors to perform measurements for NDVI analysis. Using precision agriculture as an example, the process of NDVI analysis from flight planning to results is observed.

Keywords: Agriculture, Multispectral Sensor, NDVI, UAV, Vegetation Indices

Suomenkielinen tiivistelmä: Kasvillisuusindeksejä käytetään kasvillisuuden tavoiteltujen ominaisuuksien parantamiseksi. Käyttämällä algoritmejä, kuten normalisoitua kasvillisuusindeksiä (NDVI), vihreän kasvillisuuden terveys tai stressi voidaan mitata täsmällisesti ja yhdenmukaisesti. Tämä kirjallisuuskatsaus tutkii NDVI:n lähtökohtia ja multispektrisensorilla varustettujen miehittämättömien ilma-alusten (UAV) käyttöä mittauksiin NDVI-analyysejä varten. NDVI-analyysiprosessi lentosuunnittelusta tuloksiin tarkastellaan käyttäen täsmäviljelyä esimerkkinä.

Avainsanat: Maatalous, Multispektrisensori, NDVI, UAV, Kasvillisuusindeksi

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1 Introduction

Unmanned Aerial Vehicle (UAV) technology has been rapidly developing in recent years. In the past, and still to some extent, the term "UAV" was predominantly associated with military drone technology (Sullivan 2005). The reality is that there are currently several present and emerging civil applications for UAVs (Shakhatreh et al. 2019).

According to Honrado et al. 2017, UAV based vegetation analysis is globally becoming a viable application to enhance productivity in the agricultural industry. Due to their ability to fly at low altitudes and capture high resolution imagery on multiple spectra, their convenience and affordability make UAVs the primary choice for Vegetation analysis and indexing over satellite imagery (Cevallos et al. 2018). There are several algorithms for assessing vegetation, depending on the required outcomes. A common algorithm currently used for vegetation indexing is the Normalized Difference Vegetation Index (NDVI). This study will focus primarily on the NDVI algorithm, it's applications and implementation.

NDVI from satellite imagery can have many useful applications and is more suitable in some instances, however for simplicity this thesis will focus primarily on it's use with regard to agriculture.

2 Vegetation Measurement

Historically, vegetation analysis involved a lot of manual work. Before the advent of emerging technologies, vegetation classification and fieldwork was completed manually (Gibbons and Freudenberger 2006). For example, stem density of an area can be manually measured by assessing the basal area of nearby vegetation by looking through a glass prism to record the number of trees whose trunks look displaced (Higgins et al. 2005). Manual analysis still has it's uses, however modern methods with the aid of imaging technology are becoming the preferred norm due to their accuracy and efficiency (Herrick 2017).

In recent decades with the increasing abundance and quality of satellite imagery, as low as 60-cm spatial resolution (Zhang, Du, and Zhang 2015), new ways to measure vegetation were developed. For example, in the early 1980's NASA scientists at the Goddard Space Flight Center produced the NDVI algorithm to measure biomass and other vegetation features en masse (Voiland 2009). Satellite imagery is still widely used for vegetation analysis, and will most likely remain the primary method for larger scales, such as continental analysis. However, for situations requiring extremely high resolution imagery, UAV acquisition is preferable.

Published patents for drone technology have grown since the early 2000's and have been increasing exponentially over the previous decade (Blijlevens and Lim 2014). Many of these technological advancements are targeting UAV imagery. Due to their ability to fly close to the ground, UAVs are able to capture high resolution imagery over relatively large areas of interest rapidly (Mancini, Frontoni, and Zingaretti 2019). With automated flight paths, the same area of data can be temporally acquired with minimal variation. UAVs are limited by the amount of flight time, mostly due to fuel consumption or battery capacity (Chengjun and Xiuyun 2017). UAVs are currently most suited to small to medium localised areas of interest. Fixed wing UAVs can cover more ground than rotor based UAVs, however rotary UAVs offer more precision and the ability to take off and land vertically and are generally more affordable (DroneDeploy 2017).

3 Vegetation Indices

A vegetation index is used to reliably make comparisons of a section of soil and/or vegetation, by giving it a standardised value (Chase et al. 2000). These comparisons may be applied to different geographical locations, or to the same location separated by time. Presently, with the use of remote sensing technology, vegetation indices are essentially derived from applying a transformation to two or more bands of light in order to enhance the specific vegetation properties of interest (Chase et al. 2000). For example, near infrared (NIR) and red light (R) are the 2 bands needed to meet the requirements of the Normalised Difference Vegetation Index (NDVI), because they are able to enhance the properties of green vegetation (Weier and Herring 2000).

There are other types of vegetation indices that are more applicable under certain circumstances. NDVI is a relatively basic index in it's complexity, and is commonly used in conjunction with UAV based sensory (Saari et al. 2011). However, when atmospheric disturbances and other obstructions are present there are more suitable indices that can be utilised. For example, the Enhanced Vegetation Index (EVI) is an extrapolation of the NDVI algorithm, see chapter 4.1), and takes into account factors such as aerosol resistance and de-couples the canopy background signal (Chase et al. 2000). Compared to the NDVI algorithm shown later in equation (4.1), the following EVI algorithm is slightly more complex,

$$EVI = G \times \frac{NIR - R}{NIR + C1 \times R - C2 \times B + L} \tag{3.1}$$

where NIR, R and B correspond to near infrared, red and blue light respectively. $C1$ and $C2$ are aerosol resistance co-efficients, L is a vegetation canopy adjustment and G is the gain factor. As the blue band needs to be measured for EVI, equipment measuring more than the 2 spectral bands needed for NDVI, such as the Moderate Resolution Imaging Spectroradiometer (MODIS), is required. However, MODIS is also used to measure NDVI as well as other indices (Testa et al. 2018).

A vegetation index can be classified in several ways. The method of calculation and targeted attributes are both valid ways of classifying vegetation indices, but for the purpose of this thesis the best way we would classify our vegetation index of focus (NDVI) is by the number of spectral bands it requires (Bannari et al. 1995). As the NDVI requires both the near infrared and red bands it is classified as a multispectral vegetation index (generally 2-10 bands). Further evolution of spectral imaging technology produced hyperspectral imagery with narrower bandwidths of <= 10 nm. Vegetation indices such as the moment distance index (MDI) which can be used to find spectral regions for carotenoids and chlorophyll is an example of a hyperspectral index (Salas and Henebry 2012). As the topic of this thesis is the NDVI, naturally we are only focussing on a multispectral vegetation index.

4 NDVI

The NDVI algorithm is currently the most widely used algorithm for vegetation analysis (Weier and Herring 2000). By using devices to measure multispectral reflectance, such as the reflectance of red (visible) light as well as near infrared light, we are able to use the NDVI algorithm to compare vegetation in different ways. The NDVI algorithm gives us a value of between -1 and 1. From an image, this algorithm is applied to the data gathered from each and every pixel. As shown in figure 1 values close to 0 usually represent little to no present vegetation, whereas values closer to 1 represent rich green vegetation (Crippen 1990).

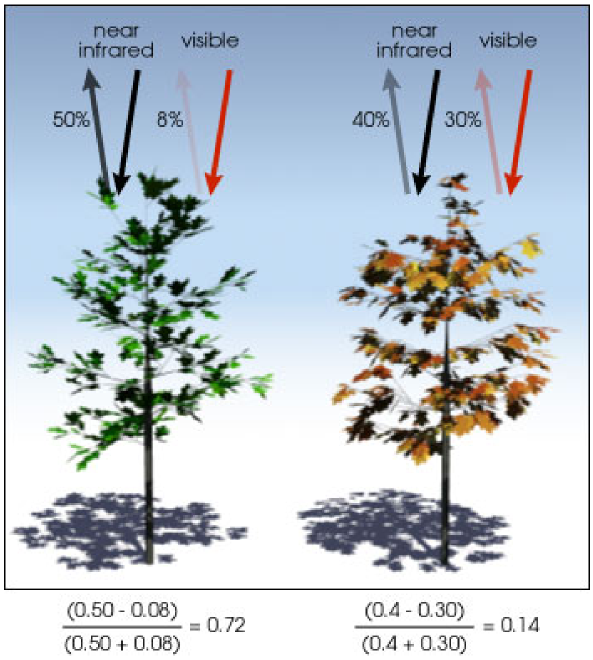

Figure 1. NDVI and green vs brown vegetation - Image courtesy of NASA (Weier and Herring 2000)

A typical agricultural implementation of NDVI is to capture multispectral imagery of a crop field and apply the algorithm to each pixel of the resulting imagery using available software. This gives a very clear visual representation, usually using a red-green scale, of the crop health from the field. This information can be used to make informed decisions about what aspects of crop production, if any, can be improved (Pratama, Hadary, and Yacoub 2017).

For example, if NDVI values are lower in a certain portion of the field, then the farmer can analyse his in place procedures to determine the root cause of the production deficiencies. This could be related to many things such as irrigation, drainage or even fertiliser application (Pratama, Hadary, and Yacoub 2017).

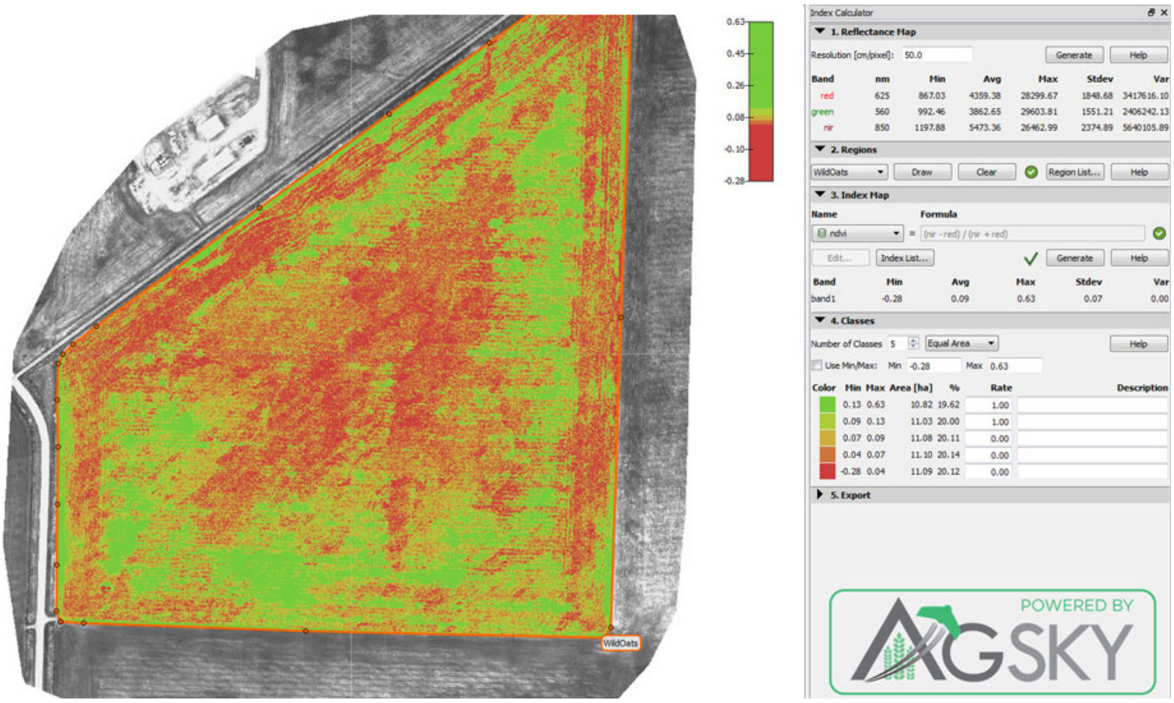

Figure 2. An example of NDVI processing software (Genik 2015)

Figure 2 shows Green Aerotech's software in action. A red-green scale is applied to the NDVI values processed for the gathered UAV imagery of a wild oat field. The scale is representative of the minimum (-0.28) to maximum (0.63) NDVI values. This visual representation is very easy to decipher even for someone who has no farming experience.

Without the NDVI analysis performed with the help of data gathered from UAV devices, making any adjustments to production processes would involve more trial and error. Crop health assessment using NDVI is much more accurate than simply making observations from photography with the naked eye (Herrick 2017).

Due to the ease and automation of UAV's - multiple analyses can be preformed to assess vegetation health. Using the NDVI results from one scan and comparing them to another will show if steps taken to improve vegetation health are effective or not. Because of the nature of the NDVI algorithm, giving a normalised value with it's difference formula, the results given make comparison very accurate (Peña and Ulloa 2017).

It is more than apparent that the NDVI algorithm is extremely useful in it's application to agriculture. Due to the increasing affordability and ease of use of UAV's, NDVI analysis is becoming more than commonplace for farmers in order to increase crop health/yield and ultimately their profit margins (Okayasu et al. 2017).

4.1 The NDVI Algorithm

Multispectral vegetation indices are those which focus on a smaller number of wider bands of light. Light bands such as red, green and infra-red are included in this classification and are thus when captured together are considered multispectral (Weier and Herring 2000). As it requires both red and near infrared reflectance to be measured, NDVI is a multispectral vegetation index and it's algorithm as a process is illustrated below in figure 3.

The NDVI equation itself is technically speaking rather straight forward and is denoted as follows,

$$NDVI = \frac{NIR - R}{NIR + R} \tag{4.1}$$

where NIR and R represent spectral reflectance ratios of incoming radiation in the form of near-infrared and red (visible) light. To be normalised these values are restricted to the range of -1 to 1. As healthy green vegetation has a higher NIR reflectance, the corresponding NDVI value will be closer to 1. Orange leaves will yield an NDVI value between 0.5 and 0. NDVI results very close to 0 will represent barren land or soil (Weier and Herring 2000). The method in which NDVI is applied is by processing equation 4.1 to each and every pixel in a captured multispectral image. If the initial NDVI value happens to be outside this range the final value is rounded to the nearest limit, as shown in figure 3.

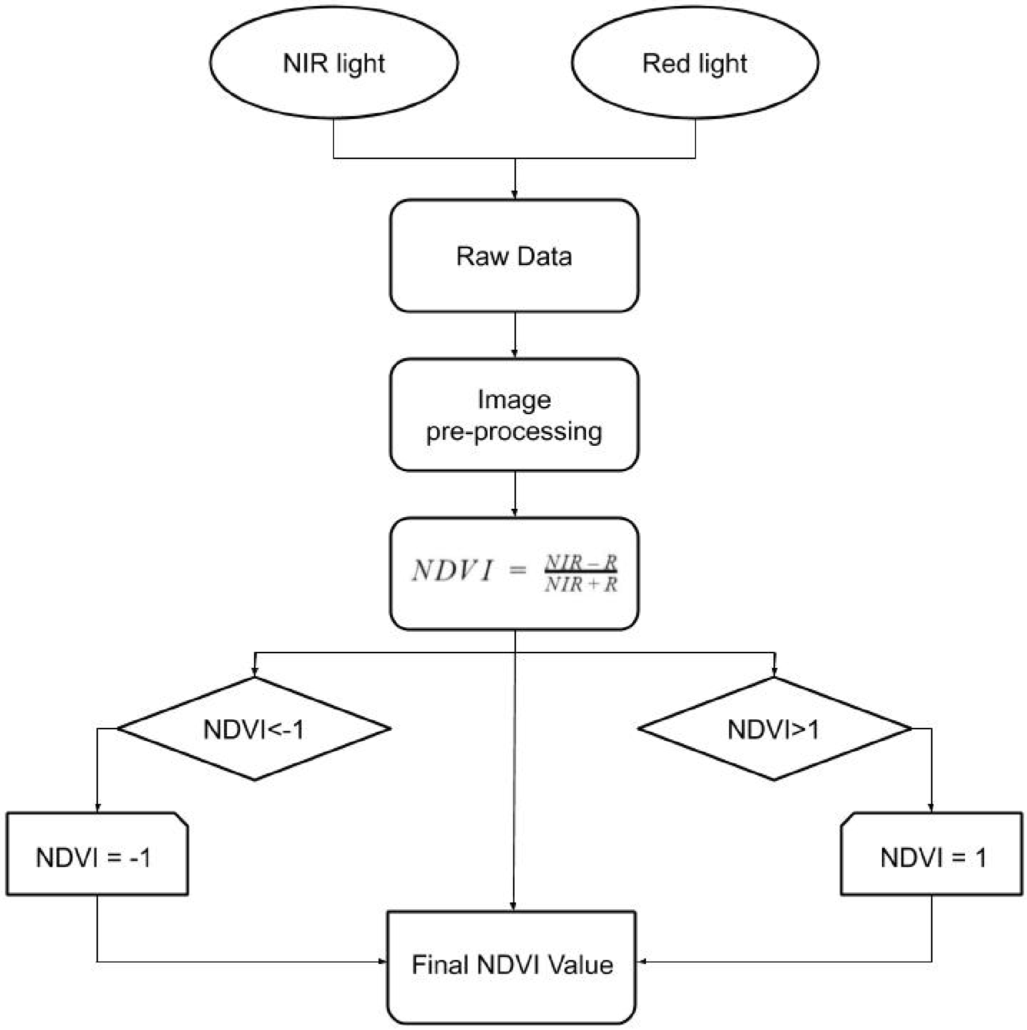

Figure 3. Simple illustration of the NDVI method

The resulting index is most commonly post-processed and output visually using a gradient of red to green (Genik 2015). The resulting product will closely resemble an aerial photo where pixels containing healthy green vegetation are represented as bright green and unhealthy vegetation pixels as orange or red, depending on their respective NDVI pixel values. An example of such an image can be seen in figure 2.

4.2 Capture Devices

As mentioned in section 3, and shown below in figure 4, the Moderate Resolution Imaging Spectroradiometer (MODIS) is a satellite payload device with high temporal, yet low spatial resolution. It is used in order to survey changes in larger scale landscapes over time (Testa et al. 2018). One of it's most common applications, among many, is the monitoring of global vegetation health and, using NDVI for example, to complete time series analyses to illustrate any trends (Lu et al. 2015). It is mounted on NASA's Terra satellite, shown below in figure 5.

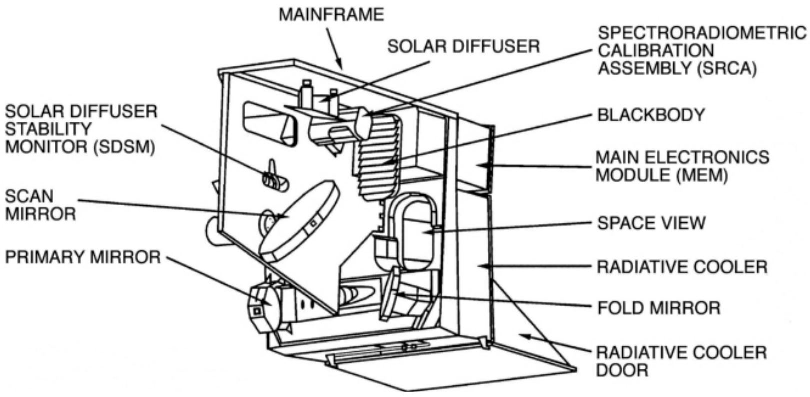

Figure 4. The MODIS instrument - the finest in engineering of spaceflight hardware for remote sensing (NASA 1995)

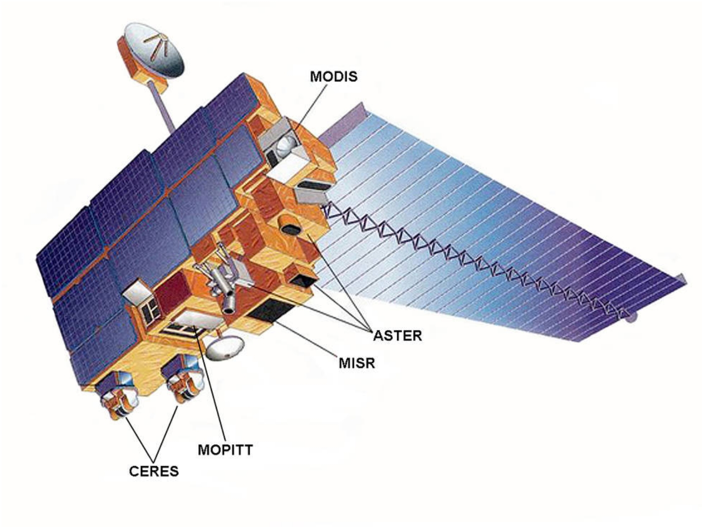

Figure 5. The MODIS unit mounted on NASA's flagship Earth Observing System Terra satellite (NASA 1999)

With the explosion of commercial UAV's for agriculture in recent decades, many devices have been developed. For NDVI analysis, depending on the size of the area of interest, a multispectral camera is equipped to either a traditional fixed wing UAV, or a rotary winged UAV as shown in figure 6. Both systems usually have some form of stabilisation mount for the camera to ensure high quality imagery (Lucieer et al. 2012).

Figure 6. An OktoKopter UAV sporting a 6-band multispectral camera (Lucieer et al. 2012)

5 Applications

5.1 Agriculture

NDVI is self defined as a vegetation index, and as far as commercial use goes, it's application is mostly focused on agriculture (Saari et al. 2011). These applications include, but are not limited to horticulture, forestry and even viticulture (Bates et al. 2018). As the objective of NDVI is to enhance and asses the greenness properties of vegetation it is becoming an integral part of many agricultural operations. UAV imagery is the most affordable and convenient method for gathering the necessary data to perform NDVI analyses (Berra, Gaulton, and Barr 2017), although some larger scale areas such as forestry may opt for satellite imagery (Hogda et al. 2002).

5.2 Other uses

Although the majority of NDVI analysis is applied to agriculture, there are many other useful applications for the algorithm.

More specialised applications of vegetation analysis include, for example, NDVI being used to assess greenness and vegetation richness in large scale Arctic regions to measure the long term effects of reindeer on the environment (Sundqvist 2019). Although much of this imagery is acquired using satellite photography rather than UAV imagery - the general principles remain the same and it is encouraging to see the use of these evolving technologies being used to monitor and combat the effects of climate change (Wang et al. 2016).

6 The NDVI Process in Precision Agriculture

With the development of UAV's, and the availability of processing software the entire process of NDVI analysis in agriculture can easily be implemented by one company or farmers can do it themselves with ready made ag-drone software packages (SENTERA 2019). The process has several key steps which are explained in this chapter.

6.1 Flight Path

In order to acquire the best possible raw data for NDVI analysis, flight path planning of the UAV is important. While it is possible to capture the required multispectral imagery for NDVI by manually flying the UAV, a fully automated flight path will ensure that 100% of the area of interest is covered efficiently and the same capture altitude while avoiding obstacles is maintained for consistent results (Yingkun 2018). There are many software packages available in the agricultural UAV market that can be used to prepare flight paths for data acquisition, for example UGCS 2019 as shown in figure 7 and DroneDeploy 2019.

Figure 7. Agricultural flight path planning with UGCS software (UGCS 2019)

Geospatial accuracy is very important in NDVI analysis. Depending on the level of accuracy required the survey may be done by using the UAV's on board Global Positioning System (GPS) and adjusted later using ground control points (Valasek, Lu, and Shi 2017). For superior accuracy however, it is common for Real Time Kinetic (RTK) GPS to be used. RTK makes use of a separate ground station that is very accurate and gives a real-time reference point to increase GPS accuracy from several metres to centimetres (Kahvecı 2017).

The flight path used may differ depending on the devices used. The type of UAV, fixed-wing vs rotary, as well as the specifications of the multispectral camera used will play a part in flight path planning. As NDVI analyses are often compared temporally, an automated flight plan is preferably as it can be easily saved and used again later (B.McNeil 2015). This ensures accurate results in terms of making comparisons.

6.2 Data Acquisition

The accuracy and quality of the data collected is arguably the most important part in the process of NDVI analysis. A decent multispectral camera, for example the parrot shown in figure 8, is needed to capture the *NIR* and *R* bands, and a UAV capable of carrying such a payload must be used.

Figure 8. The Parrot Sequoia+ multispectral camera (*Parrot SEQUOIA+ | Parrot Store Official* 2019)

The field of view of the camera will have some determination over the flight path altitude of the UAV. The frequency of image capture, for example 1 frame per second for the Parrot Sequioa+ shown in figure 8, will affect the speed at which the UAV flies. Other factors need to be taken into consideration, such as ensuring the camera is stabilised, the images are properly georeferenced and there is sufficient storage for the captured data. Captured imagery is typically stored on a SD card in a georeferenced timestamped image format for each separate band. These images are later mosaicked in pre-processing software (such as Pix4D 2019) to create on large image file for each band and are now ready for NDVI processing.

6.3 Data Analysis

Once full coverage data has been captured for the area of interest and checked for any anomalies, such as obstructions or hardware malfunctions, data analysis can now begin (Lee, Shin, and Park 2019). Through chosen processing software, which often has a built in NDVI function, the captured data can be autonomously processed through the NDVI algorithm. As images for both the *NIR* and *R* bands are georeferenced, the respective reflectance value for each band's corresponding pixels are simultaneously fed into the NDVI algorithm and output to give a single NDVI value. These values, once calculated for every pixel, are processed through a chosen red-green spectrum to visually represent the health of the crops, similar to the image shown in figure 2.

6.4 Results

The resulting data can be used in many ways. With regard to agriculture, the most common application is to assess NDVI results for any apparent crop variation (Lee, Shin, and Park 2019). This information can be used to take any action such as adjusting the levels and application of pesticides and fertilisers (Pratama, Hadary, and Yacoub 2017).

If drainage and irrigation to a crop field is not optimised, the results from regular

NDVI analysis can be used to make sure that the produce is receiving the correct amount of water. This can be extremely important in drought situations where the viability of the entire crop may be in question (Su et al. 2018). Another useful application of an NDVI analysis is to assess damage to crops after an environmental event. After the "super cold wave" in 2016 in the Guangdong province in China, vegetation analysis was performed to see the extent of the decline in NDVI values in potato fields (Liu et al. 2016).

NDVI results can additionally be used for phenological purposes. By seasonally comparing NDVI analyses, observations on climate and local environmental trends can be made (Cai, Zhang, and Zhang 2012). This information is valuable to both farmers and environmental scientists.

7 Conclusion

The methods and devices used in vegetation measurement and analysis have progressed significantly in recent decades. Traditionally vegetation was measured and classified manually, usually by ground surveys often with the use of simple instruments such as prisms to enhance some vegetation properties. Now thanks to technological advancements and organisations such as NASA, vegetation processing algorithms making use of VI's, such as NDVI, have been developed that allow us to enhance certain properties of vegetation from a simple multispectral image. This use of vegetation indices can be applied to many circumstances and used to solve many modern problems. NDVI itself can be used to enhance the properties of green vegetation to assess it's presence, and whether said vegetation is stressed or healthy. As a simple transformation of the NIR band of light, which healthy vegetation reflects, and the red band which healthy vegetation absorbs, NDVI can give a standardised value from -1 to 1 which can be used to illustrate the health of crops or other sources of green vegetation. Traditionally NDVI was used with satellite imagery on a larger scale, however now more applications are being produced. Precision agriculture using UAV's, both rotary and fixed wing, are increasingly becoming a viable method used by farmers to assess their crops regularly to make adjustments to their processes and increase crop yield. Both the affordability and ease of use of these UAV based solutions are very attractive to farmers. A UAV with accurate GPS and a basic multispectral camera along with processing software is all that is needed for farmers to accurately measure and analyse the health of their crops. Flight paths can be reused for consistency when comparing results temporally.

Bibliography

B.McNeil. 2015. *Farmers go high tech with remote sensing by SLANTRANGE.* https://www.directionsmag.com/article/1245. (Accessed on 11/28/2019).

Bannari, A., D. Morin, F. Bonn, and A. R. Huete. 1995. "A review of vegetation indices". *Remote Sensing Reviews* 13 (1-2): 95–120. doi:10.1080/02757259509532298. eprint: https://doi.org/10.1080/02757259509532298. https://doi.org/10.1080/02757259509532298.

Bates, T., J. Dresser, R. Eckstrom, G. Badr, T. Betts, and J. Taylor. 2018. "Variable-rate mechanical crop adjustment for crop load balance in 'Concord' vineyards". In *2018 IoT Vertical and Topical Summit on Agriculture - Tuscany (IOT Tuscany),* 1–4. doi:10.1109/IOT-TUSCANY.2018.8373046.

Berra, E. F., R. Gaulton, and S. Barr. 2017. "Commercial Off-the-Shelf Digital Cameras on Unmanned Aerial Vehicles for Multitemporal Monitoring of Vegetation Reflectance and NDVI". *IEEE Transactions on Geoscience and Remote Sensing* 55, number 9 (): 4878–4886. ISSN: 1558-0644. doi:10.1109/TGRS.2017.2655365.

Blijlevens, A., and J. Lim. 2014. *Patents are a virtue: droning on – stoppress.co.nz.* https://stoppress.co.nz/opinion/patents-are-virtue-droning/66/?amp=1. (Accessed on 11/28/2019).

Cai, D., X. Zhang, and S. Zhang. 2012. "Response of NDVI of spring wheat to climate warming in Minqin of China". In *2012 IEEE International Geoscience and Remote Sensing Symposium,* 6593–6596. doi:10.1109/IGARSS.2012.6352088.

Cevallos, L. N. M., J. L. R. García, B. I. A. Suárez, C. A. L. González, I. S. González, J. A. Y. Campoverde, J. A. M. Guzmán, and T. Toulkeridis. 2018. "A NDVI Analysis Contrasting Different Spectrum Data Methodologies Applied in Pasture Crops Previous Grazing - A Case Study from Ecuador". In *2018 International Conference on eDemocracy eGovernment (ICEDEG),* 126–135. doi:10.1109/ICEDEG.2018.8372375.

Chase, Mark W., Anette Y. De Bruijn, Anthony V. Cox, Gail Reeves, Paula J. Rudall, Margaret A.T. Johnson, and Luis E. Eguiarte. 2000. “ Phylogenetics of Asphodelaceae (Asparagales): An Analysis of Plastid rbcL and trnL-F DNA Sequences ”. *Annals of Botany* 86, number 5 (): 935–951. ISSN: 0305-7364. doi:10.1006/anbo.2000.1262. eprint: http://oup.prod.sis.lan/aob/article-pdf/86/5/935/7984152/860935.pdf. https://doi.org/10.1006/anbo.2000.1262.

Chengjun, Z., and M. Xiuyun. 2017. “Spare A search approach for UAV route planning”. In *2017 IEEE International Conference on Unmanned Systems (ICUS)*, 413–417. doi:10.1109/ICUS.2017.8278380.

Crippen, Robert E. 1990. “Calculating the vegetation index faster”. *Remote Sensing of Environment* 34 (1): 71–73. ISSN: 0034-4257. doi:https://doi.org/10.1016/0034-4257(90)90085-Z. http://www.sciencedirect.com/science/article/pii/003442579090085Z.

DroneDeploy. 2017. *Choosing the Right Mapping Drone for Your Business Part I: Multi-Rotor vs. Fixed Wing Aircraft.* https://blog.dronedeploy.com/choosing-the-right-mapping-drone-for-your-business-part-i-multi-rotor-vs-fixed-wing-aircraft-6ec2d02eff48. (Accessed on 11/28/2019).

———. 2019. *Drone Software for Agriculture | DroneDeploy.* https://www.dronedeploy.com/solutions/agriculture/. (Accessed on 11/28/2019).

Genik, Warren. 2015. *Case Study: Wild Oat control efficiency using UAV imagery – Green Aero Tech.* https://www.greenaerotech.com/case-study-wild-oat-control-efficiency-using-uav-imagery/. (Accessed on 11/09/2019).

Gibbons, Philip, and David Freudenberger. 2006. “An overview of methods used to assess vegetation condition at the scale of the site”. *Ecological Management & Restoration* 7 (s1): S10–S17. doi:10.1111/j.1442-8903.2006.00286.x. eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1442-8903.2006.00286.x. https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1442-8903.2006.00286.x.

Herrick, S. 2017. *Discover NDVI and Its Valuable Uses in Agriculture - Botlink.* https://botlink.com/blog/discover-ndvi-and-its-valuable-uses-in-agriculture. (Accessed on 11/28/2019).

Higgins, Kenneth, Kurt Jenkins, Gary Clambey, Daniel Uresk, David Naugle, Jack Norland, and William Barker. 2005. "Vegetation sampling and measurement" ().

Hogda, K. A., S. R. Karlsen, I. Solheim, H. Tommervik, and H. Ramfjord. 2002. "The start dates of birch pollen seasons in Fennoscandia studied by NOAA AVHRR NDVI data". In *IEEE International Geoscience and Remote Sensing Symposium,* volume 6, 3299–3301 vol.6. doi:10.1109/IGARSS.2002.1027162.

Honrado, J. L. E., D. B. Solpico, C. M. Favila, E. Tongson, G. L. Tangonan, and N. J. C. Libatique. 2017. "UAV imaging with low-cost multispectral imaging system for precision agriculture applications". In *2017 IEEE Global Humanitarian Technology Conference (GHTC),* 1–7. doi:10.1109/GHTC.2017.8239328.

Kahvecı, M. 2017. "Contribution of GNSS in precision agriculture". In *2017 8th International Conference on Recent Advances in Space Technologies (RAST),* 513–516. doi:10.1109/RAST.2017.8002939.

Lee, D., H. Shin, and J. Park. 2019. "Identification of Precision Vegetation Variations of Chinese Cabbage Using UAV and Sensors". In *IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium,* 7314–7317. doi:10.1109/IGARSS.2019.8899801.

Liu, W., S. Huang, D. Li, Chongyang Wang, and Shuisen Chen. 2016. "Temperature variation and winter planted potato's NDVI change during early 2016's super cold wave in Guangdong province, South China". In *2016 4th International Workshop on Earth Observation and Remote Sensing Applications (EORSA),* 470–473. doi:10.1109/EORSA.2016.7552853.

Lu, Linlin, Claudia Kuenzer, Cuizhen Wang, Qing Guo, and Qingting Li. 2015. "Evaluation of Three MODIS-Derived Vegetation Index Time Series for Dryland Vegetation Dynamics Monitoring". *Remote Sensing* 7 (): 7597–7614. doi:10.3390/rs70607597.

Lucieer, Arko, Sharon Robinson, Darren Turner, Steve Harwin, and Joshua Kelcey. 2012. "Using a micro-UAV for ultra-high resolution multi-sensor observations of Antarctic moss beds", volume XXXIX-B1. doi:10.5194/isprsarchives-XXXIX-B1-429-2012.

Mancini, A., E. Frontoni, and P. Zingaretti. 2019. "Satellite and UAV data for Precision Agriculture Applications". In *2019 International Conference on Unmanned Aircraft Systems (ICUAS)*, 491–497. doi:10.1109/ICUAS.2019.8797930.

NASA. 1995. *MODIS Web.* https://modis.gsfc.nasa.gov/about/components.php. (Accessed on 11/24/2019).

———. 1999. *Terra Spacecraft | NASA.* https://www.nasa.gov/mission_pages/terra/spacecraft/index.html. (Accessed on 11/24/2019).

Okayasu, T., A. P. Nugroho, A. Sakai, D. Arita, T. Yoshinaga, R. Taniguchi, M. Horimoto, E. Inoue, Y. Hirai, and M. Mitsuoka. 2017. "Affordable field environmental monitoring and plant growth measurement system for smart agriculture". In *2017 Eleventh International Conference on Sensing Technology (ICST)*, 1–4. doi:10.1109/ICSensT.2017.8304486.

Parrot SEQUOIA+ | Parrot Store Official. 2019. https://www.parrot.com/business-solutions-us/parrot-professional/parrot-sequoia. (Accessed on 11/28/2019).

Peña, M. A., and J. Ulloa. 2017. "Mapping the post-fire vegetation recovery by NDVI time series". In *2017 First IEEE International Symposium of Geoscience and Remote Sensing (GRSS-CHILE)*, 1–8. doi:10.1109/GRSS-CHILE.2017.7996002.

Pix4D. 2019. *Agricultural drone mapping: crop protection and production | Pix4D.* https://www.pix4d.com/industry/agriculture. (Accessed on 11/28/2019).

Pratama, R. W., F. Hadary, and R. R. Yacoub. 2017. "Design unmanned aerial vehicle integrated camera near infra-red to observe the plant health". In *2017 4th International Conference on Electrical Engineering, Computer Science and Informatics (EECSI)*, 1–4. doi:10.1109/EECSI.2017.8239146.

Saari, Heikki, Ismo Pellikka, Liisa Pesonen, Sakari Tuominen, Jan Heikkilä, Christer Holmlund, Jussi Mäkynen, Kai Ojala, and Tapani Antila. 2011. "Unmanned Aerial Vehicle (UAV) operated spectral camera system for forest and agriculture applications". In *Remote Sensing for Agriculture, Ecosystems, and Hydrology XIII,* edited by Christopher M. U. Neale and Antonino Maltese, 8174:170–184. International Society for Optics and Photonics, SPIE. doi:10.1117/12.897585. https://doi.org/10.1117/12.897585.

Salas, Eric Ariel L., and Geoffrey M. Henebry. 2012. "Separability of maize and soybean in the spectral regions of chlorophyll and carotenoids using the Moment Distance Index". *Israel Journal of Plant Sciences* 60 (1-2): 65–76. doi:10.1560/IJPS.60.1-2.65. eprint: https://www.tandfonline.com/doi/pdf/10.1560/IJPS.60.1-2.65. https://www.tandfonline.com/doi/abs/10.1560/IJPS.60.1-2.65.

SENTERA. 2019. *NDVI Precision Agriculture Drones & Sensors | Crop Scouting Drones.* https://sentera.com/dji-ndvi-upgrade/. (Accessed on 11/28/2019).

Shakhatreh, H., A. H. Sawalmeh, A. Al-Fuqaha, Z. Dou, E. Almaita, I. Khalil, N. S. Othman, A. Khreishah, and M. Guizani. 2019. "Unmanned Aerial Vehicles (UAVs): A Survey on Civil Applications and Key Research Challenges". *IEEE Access* 7:48572–48634. ISSN: 2169-3536. doi:10.1109/ACCESS.2019.2909530.

Su, J., M. Coombes, C. Liu, L. Guo, and W. Chen. 2018. "Wheat Drought Assessment by Remote Sensing Imagery Using Unmanned Aerial Vehicle". In *2018 37th Chinese Control Conference (CCC),* 10340–10344. doi:10.23919/ChiCC.2018.8484005.

Sullivan, J.M. 2005. "Revolution or evolution? The rise of the UAVs". In *Technology and Society, 2005. Weapons and Wires: Prevention and Safety in a Time of Fear. ISTAS 2005. Proceedings. 2005 International Symposium on,* 94–101. doi:10.1109/ISTAS.2005.1452718.

Sundqvist, Maja K. 2019. "Experimental evidence of the long-term effects of reindeer on Arctic vegetation greenness and species richness at a larger landscape scale". Edited by Ekologia ja evoluutiobiologia. ISSN: 0022-0477.

Testa, S., K. Soudani, L. Boschetti, and E. Borgogno Mondino. 2018. "MODIS-derived EVI, NDVI and WDRVI time series to estimate phenological metrics in French deciduous forests". *International Journal of Applied Earth Observation and Geoinformation* 64:132–144. ISSN: 0303-2434. doi:https://doi.org/10.1016/j.jag.2017.08.006. http://www.sciencedirect.com/science/article/pii/S030324341730171X.

UGCS. 2019. *UgCS PRO for UAV Pro's.* https://www.ugcs.com/page/pro4pros. (Accessed on 11/28/2019).

Valasek, J., H. Lu, and Y. Shi. 2017. "Development and testing of a customized low-cost unmanned aircraft system based on multispectral and thermal sensing for precision agriculture applications". In *2017 International Conference on Unmanned Aircraft Systems (ICUAS),* 1208–1216. doi:10.1109/ICUAS.2017.7991494.

Voiland, Adam. 2009. *NASA - NDVI: Satellites Could Help Keep Hungry Populations Fed as Climate Changes.* https://www.nasa.gov/topics/earth/features/obscure_data.html. (Accessed on 11/23/2019).

Wang, W., Q. Feng, H. Yu, T. Liang, and N. Guo. 2016. "Spatio-temporal change of vegetation on Tibetan Plateau based on AVHRR-NDVI data". In *2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS),* 1374–1377. doi:10.1109/IGARSS.2016.7729351.

Weier, J, and D Herring. 2000. *Measuring Vegetation (NDVI & EVI).* https://earthobservatory.nasa.gov/features/MeasuringVegetation/measuring_vegetation_2.php. (Accessed on 05/18/2019).

Yingkun, Z. 2018. "Flight path planning of agriculture UAV based on improved artificial potential field method". In *2018 Chinese Control And Decision Conference (CCDC),* 1526–1530. doi:10.1109/CCDC.2018.8407369.

Zhang, F., B. Du, and L. Zhang. 2015. "Saliency-Guided Unsupervised Feature Learning for Scene Classification". *IEEE Transactions on Geoscience and Remote Sensing* 53, number 4 (): 2175–2184. ISSN: 1558-0644. doi:10.1109/TGRS.2014.2357078.