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Automatic Boundary Extraction from RADAR Images Using Artificial Intelligence Techniques

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Abstract

The extraction of land boundaries from SAR images plays a pivotal role in advancing peace processes and comprehensive rural reform in Colombia, this article explores the application of artificial intelligence (AI) techniques to automate boundary extraction, emphasising its significance in the context of Colombia’s ongoing efforts to resolve land disputes and promote rural development, Traditional methods of delimitation are often time – consuming and prone to human error, by leveraging AI, specifically machine learning algorithms, we can achieve precise and efficient boundary extraction, reducing the need for extensive manual intervention, this automatization facilities accurate land registry updates, which are essential for fair land distribution and the resolution of territorial conflicts.

1. Introduction

Colombia has faced a prolonged conflict over land, a core issue that has fuelled decades of violence and social unrest. Land disputes, often rooted in historical inequalities and unclear land ownership, have been a significant barrier to achieving lasting peace and rural development, accurate and up to date information on land rights is crucial for resolving this disputes and ensuring fair land distribution, however, traditional methods of land boundary delineation are labour intensive, time consuming and susceptible to human error, necessitating more efficient and reliable approaches. Enemark et al., (2014) highlight how to use of technologies such as orthophotos has improved fieldwork capabilities in terms of the number of plots surveyed per day in countries like Namibia.

Synthetic Aperture SAR (SAR) imagery, with its ability to penetrate cloud cover and dense vegetation, offers a robust solution for capturing detailed and consistent land information (Crommelinck et al., 2019). Unlike optical images, SAR can provide clear data regardless of weather conditions or time of day, making it an invaluable tool for continuous land monitoring; the application of Artificial Intelligence (AI) techniques, particularly machine learning algorithms, further enhances the potential of SAR imagery by enabling the automatic extraction of land boundaries with high precision and efficiency.

By automating the boundary extraction process, AI reduces the reliance on manual interventions, thus minimising errors and speeding up the updating of land registries, this technological advancement ins especially pertinent in Colombia´s contexts, where authors like Wassie et al., (2016) agree that property boundaries can be delineated by features such as buildings, roads, hedges and crop types. This paper delves into the application of AI for automatic boundary extraction in SAR images, highlighting its transformative impact on Colombia´s efforts to address land disputes and promote rural reform.

2. Materials and methods

2.1. Study area

Vista Hermosa is a municipality located in the Meta department of Colombia, situated in the central region of the country, the town is positioned in the eastern foothills of the Andes mountains and forms part of the Orinoquia region, characterised by its vast plains and rich biodiversity, Vista Hermosa is strategically located, bordered by the municipalities of La Macarena, Puerto Rico, and San Juand de Arama, making it a important area within Meta.

The economy of Vista Hermosa is primarily based on agriculture and livestock farming, the region´s fertile soils and favourable climate conditions support the cultivation of crops such as maize, rice, bean, and various fruits. In addition to crop farming, cattle ranching is a significant economic activity, contributing to the local economy through the production of meat and dairy products.

Vista Hermosa has been profoundly affected by Colombia's armed conflict, particularly dye to its strategic location and valuable agricultural land, for decades, the region was a stronghold for various guerrilla groups, including the Revolutionary Armed Forces of Colombia (FARC), the presence of these groups led to numerous violent incidents, forced displacements, and land seizures, causing significant social and economic disruption. The municipality was heavily impacted by cultivation of illicit crops and the presence of landmines, further complicating the lives of its inhabitants.

The singing of the peace agreement between the Colombian government and the FARC in 2016 marked a turning point for Vista Hermosa, the agreement aimed to address land issues and promote rural development as part of the comprehensive rural reform, efforts to clear landmines, support displaced populations, and formalise land ownership are ongoing, whit the goal of fostering long-term peace and prosperity in the region; despite these challenges Vista Hermosa is gradually recovering and working towards rebuilding its community and economy.

2.2. Methodological design

This study utilises high-resolution SAR images to automate the extraction of land boundaries, specifically employing SAR imagery from Capella Space, whit a spatial resolution of 50 centimetres, these images offer detailed and consistent data essential for accurately delineating land boundaries, even in challenging conditions such as dense vegetation or cloud cover.

The methodological framework for this study aligns with the guidelines established by the Colombian Geographic Institute (IGAC), according to Resolution 643 of 2018, land boundaries in Colombia are generally defined by natural or artificial elements, which are usually visible in images, this resolution provides a crucial foundation for identifying and delineation land boundaries based on recognizable features such as rivers, roads, and constructed fences, by leveraging the high-resolution capabilities of Capella SAR images, these elements can be detected with greater precision, enhancing the accuracy of boundary extraction.

Additionally, resolution 1040 of 2023 from the IGAC grants cadastral managers the flexibility to apply indirect methods for collecting cadastral information, this provision supports the use of advanced technologies such as AI and remote sensing in cadastral surveying. The combination of AI techniques and high-resolution SAR imagery facilitates an efficient and reliable process for boundary extraction, reducing the need for extensive fieldwork and manual delineation, machine learning algorithms are trained to recognize and extract boundary features from the SAR images, streamlining the cadastral updating process and ensuring compliance with IGAC regulations.

2.3. Materials

Capella Space SAR images have a spatial resolution of 50 centimetres. Constellation operates in the X-band frequency and planet labs offer optical imagery with a spatial resolution of approximately 3-5 metres, captured in multiple spectral bands. Both Capella and Planet images provide complementary data sources for comprehensive land monitoring and boundary extraction, the high resolution and all-weather capabilities of SAR imagery, and offer a robust dataset for accurate and efficient land boundary delineation and monitoring. These images were generously donated by Procalculo Prosis, further supporting the project goals.

2.4. Methods

2.4.1 Artificial Intelligence

AI refers to the simulation of human intelligence processes by machines, especially computer systems (McCarthy, 2007), these processes include learning (the acquisition of information and rules for using it), reasoning (using rules to reach approximate or definite conclusions), and self-correlation. AI encompasses a wide range of technologies and techniques that enable computers to perform tasks that traditionally require human intelligence, these tasks include visual perception, speech recognition, decision-making, language translation, and more.

AI can be broadly categorised into two types: narrow AI and general AI, the first known as weak AI, is designed to perform specific tasks, such as facial recognition or internet searches. General AI, also known as strong AI, aims to perform any intellectual task that a human can do, though this level of AI remains largely theoretical and is a topic of ongoing research.

Machine Learning (ML) is defined as a subfield of artificial intelligence that focuses on how computers acquire knowledge from large datasets. It arises from convergence of statistics and computer science, with the purpose of identifying relationships within the data using efficient computational algorithms (Deo, 2015)

In the context of land boundary extraction, machine learning algorithms can be trained to recognize and delineate boundaries from high resolution SAR images, these algorithms analyse patterns and features within the imagery to accurately identify natural and artificial elements that define land parcels significantly improving the efficiency and accuracy of cadastral mapping and updating processes.

2.4.2 Processing

Speckle Correction: Speckle is a granular noise that inherently exists in and degrades the quality of SAR images (Mahdavi, 2017), including SAR imagery; it is caused by the coherent nature of SAR wave reflections from multiple scatterers within each resolution cell. Speckle appears as salt and pepper noise, reducing the interpretability of SAR images and complicating the process of automatic boundary extraction, effective speckle correction techniques are crucial to enhance the quality of SAR images and improve subsequent image analysis tasks, the filter with the best results was IDAN.

The improved detail preserving adaptive neighbourhood (IDAN) filter is an advanced speckle reduction method designed to mitigate the effects of speckle noise while preserving important image details and edges, this filter adapts to the local statistical properties of the image, making it particularly effective for SAR imagery, the equations used in the IDAN filter are:

A. **Adaptive Neighbourhood Selection:** Based on the local statistics of the image for each pixel i in the image, a neighbourhood $N(i)$ is determined adaptively based on the similarity of pixel intensities within a predefined window.

B. **Similarity Measure:** The similarity between the central pixel i and a neighbouring pixel j is typically measured using a similarity function:

$$S(i,\ j) = exp\left(-\ \frac{|I(i)-I(j)|^2}{2\alpha^2}\right)$$

Where:

- $I(i)$and $I(j)$ are the intensities of the central pixel i and the neighbouring pixel j, respectively.

- α is a parameter controlling the sensitivity to intensity differences.

C. **Weights calculation:** The weight $w(i,\ j)$ for each neighbouring pixel j in the adaptive neighbourhood $N(i)$ is computed based on the similarity function $S(i,\ j)$

$$w(i,\ j) = \frac{S(i, j)}{\Sigma_{k=N(i)} S(i, k)}$$

Where the denominator is the normalisation factor ensuring that the weights sum to 1

D. **Weighted Mean Calculation:** The filtered intensity $\dot{I}(i)$ for the central pixel i is calculated as the weighted mean of the intensities in the adaptive neighbourhood:

$$\dot{I}(i) = \Sigma_{j\in N(i)} w(i,\ j) I(j)$$

E. **Final IDAN Equation:** Combining the steps above the IDAN filtering process can be summarised by the equation:

$$\dot{I}(i) = \Sigma_{j\in N(i)} \left(\frac{\exp exp\left(-\frac{|I(i)-I(j)|^2}{2\alpha^2}\right)}{\Sigma_{k\in N(i)} \exp exp\left(-\frac{|I(i)-I(j)|^2}{2\alpha^2}\right)} \right) I(j)$$

This equation represents the adaptive weighted mean of the pixel intensities in the neighbourhood, where the weights are determinate based on the similarity on pixel intensities, IDAN filter effective reduces speckle noise while preserving important details edges in the SAR images

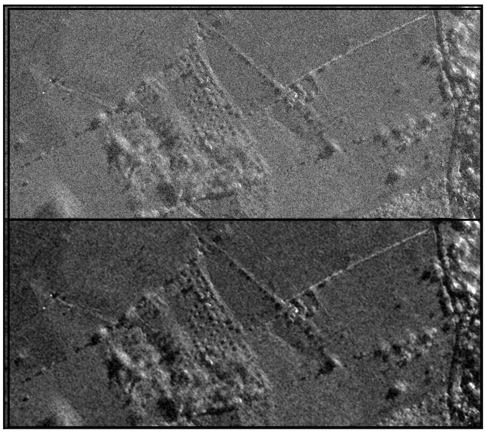

Figure 1. Noise filtering

Synergism: As mentioned by Eibedingil et al,. 2021 the fusion of SAR and optical images leverages the complementary strengths of both types of remotes sensing data, enhancing the overall quality and utility of the information derived from them, this synergistic approach combines the all-weather, day and night capabilities if SAR imagery with the high spatial and spectral resolution of optical images, resulting in more accurate and comprehensive land boundary delineation, the methodology for image fusion was:

a. **Preprocessing:** Both SAR and optical images must be geometrically corrected to ensure they are accurately aligned with each other and adjust the values of the images to ensure consistency removing any radiometric distortion.
b. **Speckle reduction:** Apply the IDAN filter to the SAR images to reduce the speckle noise.
c. **Image registration:** Precisely align the SAR and optical images to ensure they overlap accurately.
d. **Pansharpening:** This technique merges the high-resolution SAR on the optical image with lower resolution multispectral bands, enhancing the spatial resolution of the optical data, resulting image retains the spectral information while benefiting from improved spatial detail.

The fusion of SAR and optical images significantly improves the extraction of land boundaries, the combined dataset provides a more complete and accurate representation of the terrain, facilitating the identification of natural and artificial boundary markers such as rivers, roads, and fences; this enhanced accuracy is particularly beneficial in regions like Vista Hermosa, Meta where reliable land boundary information is crucial for resolving disputes and supporting rural reform.

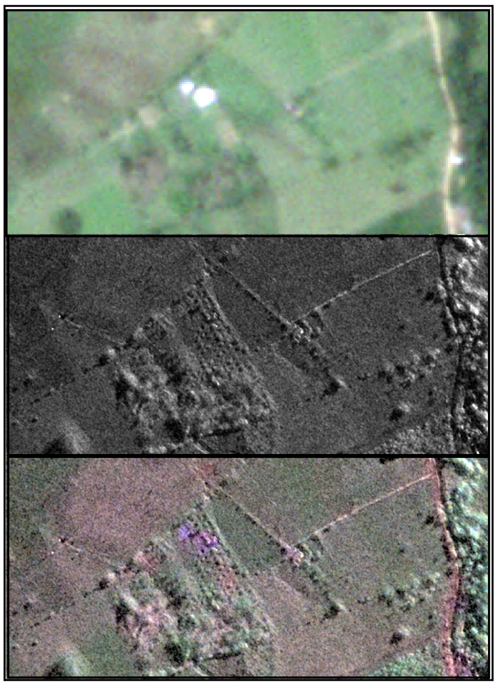

Figure 2. Synergism

Segmentation: A crucial step in the process of automated boundary extraction transforming raw image data into meaningful objects that can be analysed and classified, ArcGIS Pro offers tools for image segmentation, enabling the efficient delineation of land boundaries by using the segmentation capabilities of SIG, this study ensures the effective transformation of raw image data into meaningful segments (Prasanna C., 2023), which are essential for accurate and efficient land boundary extraction, the step by step was:

a. **Data preparation:** Load the pre-processed images and configure the environment settings, including the spatial reference system and processing extents, to match the study area.

b. **Image Segmentation:** Use the "Segment Mean Shift" tool in ArcGIS Pro, this tool clusters pixels based on their spectral and spatial characteristics, creating homogeneous regions (segments), parameters configuration:
   - **Spectral detail:** Control the sensitivity of the segmentation to differences in pixel values, higher values result in more detailed segments.
   - **Spatial detail:** Define the importance of spatial proximity between pixels, higher values emphasise the spatial continuity of segments.
   - Minimum segment size: Define the minimum segment size to merge smaller segments into larger ones, reducing noise and irrelevant details.

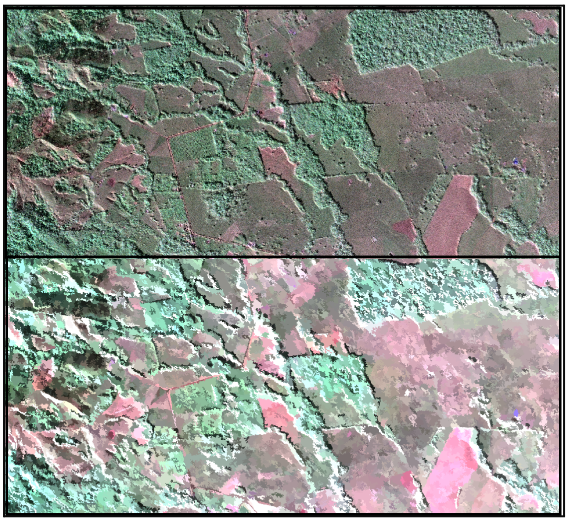

Figure 3. Segmentation

DEM: Digital Elevation Models (DEMs) are crucial for a variety of geospatial analyses, including land boundary extraction, terrain analysis, and landscape modelling; SARgrammetry involves the use of SAR images to derive 3D spatial information, similar to how photogrammetry uses optical images, this technique is particularly useful for creating Digital Elevation Models (DEMs) and analysing terrain features, especially in areas where optical imagery is limited due to cloud cover or low light conditions.

- **Stereo Pair Creation:** Select SAR image pairs taken from different angles
- **Parallax Measurement:** Match corresponding points between the images and measure parallax for depth calculation.
- **Elevation Calculation:** Use triangulation based on parallax to calculate elevation and generate a Digital Elevation Model (DEM).
- **Post-Processing:** Smooth the DEM and assess its accuracy against known terrain data.

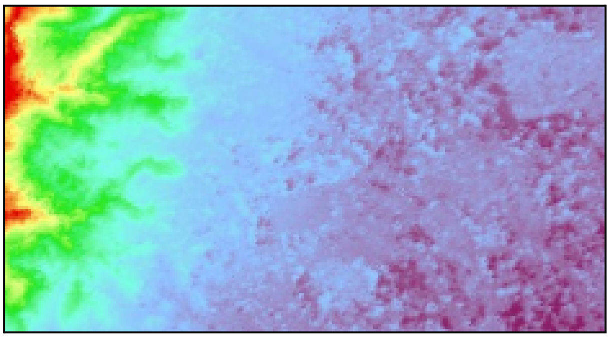

Figure 4. Generated DEM

3. Results

Classification is the final step in the process of land boundary extraction, transforming raw image data into meaningful classes that can be analysed and used for delineating boundaries, the "Detect Objects Using Deep Learning" tool in ArcGIS Pro provides advanced capabilities for automating this classification process through the application of machine learning and deep learning models, this section outlines the methodology for create a model.

- **Data preparation:** Use the fused SAR and optical images as input data and prepare training datasets that include labelled examples of different land features, such as natural boundaries (rivels, forest...) and artificial boundaries (road, fences...)
- **Model selection:** Choose a suitable AI model from the available options in ArcGIS Pro, such as convolutional neural networks (CNN) or other deep learning models.
- **Training the model:**
  - o Data Augmentation: Apply data augmentation techniques to the training data to increase its diversity and improve model robustness.
  - o Model training: Train the AI model using the prepared training dataset, configure the training parameters, such as learning rate, batch size, and number of epochs, to optimise model performance.
  - o Validation: Split the training data into training and validation sets to monitor the model´s performance and prevent overfitting, use metrics such as accuracy, precision, recall and F1 score to evaluate the model.
- **Feature extraction:** Use the "Detect Objects Using Deep Learning" tool in ArcGIS Pro to apply the trained AI model to the input images.
- **Post-processing:** Inspect the extracted features and manually refine boundaries where necessary, additionally can merge and simplify polygons.

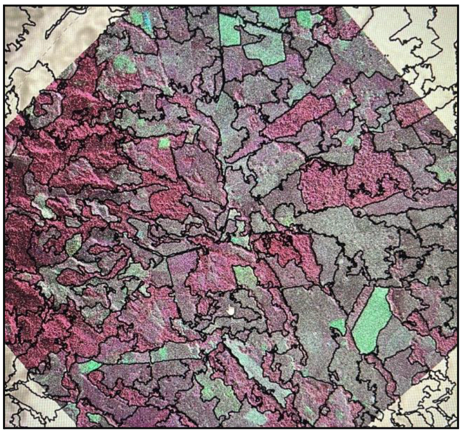

Figure 5. Preliminary Boundaries

4. Conclusions

The successful extraction of land boundaries using advanced techniques such as SAR and optical image fusion, stereo SAR processing, and AI models demonstrates the potential of these technologies to significantly enhance land management and support rural reform initiatives in Colombia, the following conclusions summarise the key findings and implications of this article:

a. The fusion of SAR and optical images combines the strengths of both data types, resulting in a dataset that offers high spatial resolution and all-weather, day-and-night capabilities, this synergistic approach improves the accuracy and reliability of and boundary delineation, ensuring that natural and artificial boundaries are accurately captured even in challenging environments.

b. The generation of digital terrain models through SARgrammetry is crucial for the automatic extraction of boundaries, as it provides high-precision elevation data that enhance accuracy and efficiency in delineating property lines, this technology minimises manual interventions making it an essential tool in large-scale land surveying and management projects.

c. Apply Segment Mean Shift enables the efficient segmentation of high-resolution imagery by grouping pixels with similar spectral and spatial characteristics; this process enhances the delineation of natural and man-made features, such as property boundaries, by creating distinct segments.

d. The "Extract Features Using AI Models" tool in ArcGIS Pro automates the classification and boundary extraction process, significantly reducing the time and effort required for manual digitalization, AI models trained on local data provide highly accurate classifications, capturing complex patterns in the imagery and delivering reliable boundary delineations, this automation supports scalable and efficient land mapping projects.

e. Accurate and reliable land boundary information is critical for supporting rural reform and resolving land disputes in Colombia, the methodologies and technologies employed in this work provide a robust framework for generating detailed and precise land boundary maps, essential for implementing comprehensive rural reform policies, promoting sustainable land management, and fostering peace in regions affected by land conflicts.

f. The integration of various advanced technologies, including SAR and optical image fusion demonstrates the potential for comprehensive and innovative approaches to land boundary extraction, the successful application of these technologies highlights the importance of continuous innovation and adaptation in geospatial sciences to address complex land management challenges.

5. Recommendations for Future Work

To further advance the methodologies and enhance the outcomes of land boundary extraction, several keys areas require attention, firstly, conducting extensive field validation and ground truthing is essential to verify the accuracy of the extracted boundaries and improve the robustness of the methodologies, this process will ensure that the generated maps accurately reflect the real-world terrain and boundaries, thereby increasing their reliability for land management and rural reform purposes.

Secondly, integrating additional data sources such as LiDAR and high-satellite imagery can significantly enhance the accuracy and detail of land boundary maps, these additional data sources offer complementary information that can fill gaps and provide more comprehensive insights into the terrain and land features.

Thirdly, adapting and applying the developed methodologies to other regions with similar land management challenges is crucial by extending the application of these techniques beyond Colombia, it is possible to address land boundary issues in various geographical contexts, thereby broadening the impact and utility of the work.

Lastly, there is a need for continuous improvement and updating of AI models, incorporating new training data and advanced algorithms wile help maintain high accuracy and ensure the models remain effective in adapting to changing landscapes. Continuous innovation in AI technologies will support the development of more sophisticated and precise lad boundary extraction methods.

References

Instituto Geografico Agustin Codazzi 2023: Resolución 1040 de 2023. "Por medio de la cual se expide la Resolución Única de la

Gestión Catastral Multipropósito.” Instituto Geográfico Agustín Codazzi - IGAC. Disponible en: https://www.alcaldiabogota.gov.co/sisjur/normas/Norma1.jsp?i=149779

Departamento Nacional de Planeación 2022: Plan Nacional de Desarrollo 2022-2026 “Colombia Potencia Mundial de la Vida”. https://colaboracion.dnp.gov.co/CDT/Prensa/Publicaciones/plan-nacional-de-desarrollo-2022-2026-colombia-potencia-mundial-de-la-vida.pdf

Instituto Geografico Agustin Codazzi 2018: Resolución 643 de 2018 "Por la cual se adoptan las especificaciones técnicas de levantamiento planimétrico para las actividades de barrido predial masivo y las especificaciones técnicas del levantamiento topográfico planimétrico para casos puntuales." https://antiguo.igac.gov.co/sites/igac.gov.co/files/normograma/resolucion_igac_643-18_adopta_especificaciones_tecnicas_levantamientos_planimetricos_y_topograficos_0.pdf

Crommelinck, S., & Koeva, M. N. 2019: Towards cadastral intelligence? Extracting visible boundaries from UAV data through image analysis and machine learning. *GIM International*. https://www.gim-international.com/content/article/towards-cadastral-intelligence

Crommelinck, S., Koeva, M., Yang, M. Y., & Vosselman, G. (2019). Application of deep learning for delineation of visible cadastral boundaries from remote sensing imagery. *Remote Sensing*, 11(21), 2505. https://doi.org/10.3390/rs11212505

Departamento Nacional de Estadística. (n.d.). Proyecciones de población. DANE. https://www.dane.gov.co/index.php/estadisticas-por-tema/demografia-y-poblacion/proyecciones-de-poblacion

McCarthy; Jhon. (2007), What is artificial Intelligence, https://www-formal.stanford.edu/jmc/whatisai.pdf.

Eibedingil I.; Gill E.; Van Pelt S.; Tong D.; Combining Optical and SAR Satellite Imagery to Investigate the Surface Properties and Evolution of the Lordsburg Playa, New Mexico, USA. https://www.mdpi.com/2072-4292/13/17/3402

Prasanna C.; Natarajan K.; Madhuri S.; Thylore M.; Rohith C.; Kumar V.; Image Processing Using Feature-Based Segmentation Techniques for the Analysis of Medical Images; https://www.mdpi.com/2673-4591/59/1/100

Enmark, S.; Bell, K. C.; Lemmen, C.; McLaren , R. Fit-For-Purpose Land Administration. Copenhague: International Federation of Surveyors, 2014. *The World Bank and the International Federation of Surveyors (FIG)* 2014. https://www.fig.net/resources/publications/figpub/pub60/Figpub60.pdf

Mahdavi S. (2017). Speckle filtering of Synthetic Aperture SAR images using filters with object-size-adapted windows. *Taylor & Francis.* https://www.tandfonline.com/doi/full/10.1080/17538947.2017.1351582#abstract

Lubeck, D. Airborne Dual-band SAR for Cadastre. *GIM International*, 2016. p. 26-27. https://www.gim-international.com/content/article/airborne-dual-band-SAR-for-cadastre

Wassie, Y.; Koeva, M.; Bennet, R. Towards Automated Detection of Visual Cadastral Boundaries. *GIM International*, 2016. p. 23-25. https://www.gim-international.com/content/article/towards-automated-detection-of-visual-cadastral-boundaries?output=pdf

Xia, X., Persello, C., & Koeva, M. (2019). Deep fully convolutional networks for cadastral boundary detection from UAV images. *Remote Sensing*, 11(14), 1725. https://doi.org/10.3390/rs11141725

Deo, Rahul C.2015, Machine Learning in Medicine. *Circulation* 132 (20): 1929-30. https://doi.org/10.1161/CIRCULATIONAHA.115.001593.