UNIVERSIDAD DISTRITAL
FRANCISCO JOSÉ DE CALDAS

Tecnura

https://revistas.udistrital.edu.co/index.php/Tecnura
DOI: https://doi.org/10.14483/22487638.20628

INVESTIGACIÓN

Design and Initial Development of a Virtual Learning Object for Self-Directed Learning in Land-Use and Land-Cover Mapping

Diseño y desarrollo inicial de un objeto virtual de aprendizaje para el aprendizaje autónomo en la elaboración de mapas de uso y cobertura del suelo

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Fecha de Recepción: 23 de marzo de 2023 **Fecha de Aceptación**: 16 de abril de 2026

Cómo citar: J. A. Valero-Medina and J. L. Herrera-Escorcia, "Design and initial development of a virtual learning object for self-directed learning in land-use and land-cover mapping," *Tecnura*, 30(89), xx-xx. https://doi.org/10.14483/22487638.20628

Abstract

Objective: To design and implement the first phase of a virtual learning object (VLO) that supports asynchronous interaction between tutors and students and enables quality assessment of student-produced land-use and land-cover maps.
Methodology: An open-source web environment was developed to manage the learning process from the initial assignment to final submission. The environment supports automated assessment of geometric and semantic consistency.
Results: The environment was tested with students in the GEIPER Remote Sensing and Geographic Information Systems research group, which is affiliated with the NIDE Spatial Data Research Group at Universidad Distrital Francisco José de Caldas. The tests used recent 0.5 m-resolution Capella radar imagery of Cáqueza, Cundinamarca, Colombia, and involved students in Cadastral Engineering and Geodesy.
Conclusions: The tests indicate that the proposed environment is a sustainable alternative for improving teaching and learning in the Earth sciences, particularly the development of skills required to produce high-quality land-use and land-cover maps.

Keywords: land-cover mapping, land-use mapping, semantic segmentation, self-directed learning, virtual learning object

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RESUMEN

Objetivo: Diseñar e implementar la primera fase de un objeto virtual de aprendizaje (OVA) que facilite la interacción asíncrona entre tutores y estudiantes y permita evaluar la calidad de los mapas de uso y cobertura del suelo elaborados por los estudiantes.
Metodología: Se desarrolló un entorno web de código abierto para gestionar el proceso de aprendizaje desde la asignación inicial hasta la entrega final. El entorno permite evaluar de manera automatizada la consistencia geométrica y semántica.
Resultados: El entorno se probó con estudiantes del semillero de investigación GEIPER en Teledetección y Sistemas de Información Geográfica, adscrito al grupo de investigación NIDE en Datos Espaciales de la Universidad Distrital Francisco José de Caldas. Las pruebas utilizaron imágenes de radar recientes de Capella, con una resolución de 0,5 m, correspondientes a Cáqueza, Cundinamarca, Colombia, y contaron con la participación de estudiantes de Ingeniería Catastral y Geodesia.
Conclusiones: Las pruebas indican que el entorno propuesto constituye una alternativa sostenible para mejorar los procesos de enseñanza y aprendizaje en ciencias de la Tierra, en particular el desarrollo de las competencias necesarias para producir mapas de uso y cobertura del suelo de alta calidad.

Palabras clave: aprendizaje autónomo, mapas de cobertura del suelo, mapas de uso del suelo, objeto virtual de aprendizaje, segmentación semántica

INTRODUCTION

Land-use and land-cover maps are essential tools for governments and nongovernmental organizations because they reveal changes on the Earth's surface and support the allocation of limited resources under local, national, and international land-use plans. Producing these maps requires both theoretical knowledge and practical expertise. Practitioners must select an appropriate classification ontology, level of detail, and minimum mapping unit for each study. In conventional teaching and learning processes, tutors must therefore monitor students individually to determine whether they have acquired the expertise required to complete such projects independently.

This paper presents the first phase in the development of an open-source VLO that supports asynchronous interaction between tutors and students and assesses the geometric and semantic quality of student-produced land-use and land-cover maps. A web-based environment manages the process from the initial assignment to final submission and automates consistency assessment using the boundary-based evaluation framework introduced in [1]. The environment was tested in the GEIPER Remote Sensing and Geographic Information Systems research group, which is affiliated with the NIDE Spatial Data Research Group at Universidad Distrital Francisco José de Caldas.

The initial implementation used recent 0.5 m-resolution Capella radar imagery of the municipality of Cáqueza, Cundinamarca, Colombia, with students in Cadastral Engineering and Geodesy. The results support the proposed environment as a sustainable means of improving teaching and learning in the Earth sciences, particularly for the challenging task of developing the skills needed to produce high-quality spatial information. Although the present work focuses on land-use and land-cover mapping, the environment can be adapted to teach basic and thematic cartography.

The remainder of this paper reviews the relevant background, describes the datasets and methodology, presents the results, and concludes with limitations and directions for future work.

Background

Virtual learning objects are increasingly used to support teaching and learning by promoting learner autonomy and knowledge management. Mejias et al. [2] implemented VLOs in higher education to complement synchronous instruction, monitor learning activities, and develop generic competencies such as autonomous learning and knowledge management. Their results indicate that greater use of information and communication technology (ICT) in higher education can improve academic performance. Following this approach, the present study uses a VLO to support the photointerpretation of digital Earth-surface imagery and to enable self-assessment in both tutor–student and collective knowledge-construction settings.

Nurbekova et al. [3] reviewed studies indexed in Web of Science, Google Scholar, and Scopus and found that VLOs can improve student learning. Their pedagogical experiment examined the effects of VLOs on educational content and learning outcomes, treating these objects not only as instructional resources but also as mechanisms for assessing acquired knowledge. The present research extends this line of work to land-use and land-cover mapping.

The evaluation frameworks proposed in [1, 4] provide an empirical basis for validating the quality of segmentations produced by image-segmentation algorithms. They score boundary-detection results, thereby enabling comparisons among different segmentations of the same image. The method can be applied to any dataset containing segment boundaries.

Building on these studies, the proposed framework determines how closely the boundary map of one segmentation matches the boundaries of another segmentation of the same image, whether or not the latter is treated as ground truth. The comparison produces two measures: precision and recall. Precision indicates the proportion of detected boundaries that correspond to boundaries in the comparison segmentation and therefore reflects boundary noise. Recall indicates the proportion of boundaries in the comparison segmentation that are recovered and therefore reflects the degree of agreement between the two segmentations.

Martin et al. [1] summarize segmentation performance with the F-measure, the harmonic mean of precision and recall. The extended framework presented by Arbeláez et al. [4] includes three additional metrics: the optimal dataset scale (ODS), which is the best F-measure obtained using a fixed scale for the entire dataset; the optimal image scale (OIS), which aggregates the best F-measure obtained separately for each image; and average precision (AP), equivalent to the area under the precision–recall curve.

In 2010, the International Federation of Surveyors (FIG) promoted e-learning for the education and continuing professional development of surveyors [5]. This policy implied substantial and inclusive changes in educational institutions, programs, and courses related to land administration. Groenendijk et al. [6] argued that these changes should strengthen institutional capacity in both the public and private sectors while improving individual assessment and professional-development capabilities.

The present proposal aims to strengthen professional capacity, initially among cadastral and geodetic engineers in Colombia, through a virtual library that supports comparison of segmentations derived from optical and radar imagery. The initial experiments used Capella radar imagery of a Colombian municipality [7]. The imagery was made available under a 2020 agreement between Universidad Distrital Francisco José de Caldas and Procalculo Prosis S.A.S. for analyzing radar data used to produce and update maps of rural homogeneous physical zones. The broader project included land-use and land-cover mapping, stereoscopic image products, digital elevation models, geocoded imagery, and slope maps.

During tests with student researchers at Universidad Distrital Francisco José de Caldas, the image bank was evaluated not only as a resource for professionals assessing segmentation software but also as a VLO for the Radar Systems course. The results reported here arise from that educational setting, although the environment may also support cooperative and collaborative work by professional teams.

Figure 1. RADARSAT-2 image used in the tutor–student reference-segmentation experiment.
Source: Authors' data.

DATA

Two satellite images were used in the segmentation experiments. For the tutor–student approach, a 2015 RADARSAT-2 image of the Bogotá savanna in Cundinamarca was assigned to six students enrolled in the Radar Systems course (Fig. 1); its metadata are listed in Table 1.

The semantic level of detail corresponded to level 2 of the field-classification system established by the Instituto Geográfico Agustín Codazzi (IGAC).

For the collective knowledge-construction approach, a Capella radar image of the municipality of Cáqueza, Cundinamarca, was used [7]. The image (Fig. 2) was segmented by students in two iterations; four students participated in the second iteration. Table 2 lists the image metadata.

Table 1. RADARSAT-2 image metadata

Item	Value
SAR Frequency Band	C
Instruments	Radarsat-2
Datetime	2015-06-09T23
SAR Instrument	Mode Ultrafine
SAR Center Frequency	5.404 GHz
SAR Polarizations	HH
SAT	Orbit state: descending
SAR Product Type	SGF
SAR Pixel Spacing Range & Azimuth	1.56 m
SAR Looks Range	1
SAR Looks Azimuth & Equivalent Number	1
SAR Resolution Range	1.6 m
Resolution Ground Range	4.6 m
SAR Resolution Azimuth	2.8 m
Incidence, Look & Squint Angles	34.7°, 37.6°, -0.0001°
Orbital Plane	97°
SAR Observation Direction	Right
Collect Id	PDS 04838400
Product Category	custom
Billable Area	40000000

Source: Authors' data.

Figure 2. Capella radar image used in the collective knowledge-construction experiment.
Source: [7].

For this experiment, the semantic level of detail corresponded to level 3 of the IGAC classification system.

METHODOLOGY

Because the framework in [1] assesses segmentation geometry by comparing detected boundaries with reference boundaries, the proposed self-directed learning tool adopts two complementary approaches: (i) assessing the relative consistency of a segmentation against a reference set and (ii) assessing the internal consistency of a set by comparing every pair of segmentations. Thematic consistency was calculated from confusion matrices with 95 % confidence intervals. For brevity, the figures in the Results section report only overall thematic consistency.

The first approach enables a tutor to assess student performance by comparing the student's segmentation with a reference segmentation. The second compares every pair of segmentations in a set and thus supports collective knowledge construction: students can observe the consistency of the group output. Low consistency indicates substantial disagreement, whereas high consistency indicates convergence toward a shared interpretation.

The system architecture was designed to support asynchronous work by tutors and students, collective knowledge construction, access without proprietary software, and basic security requirements that permit sustainable growth of the user community. The adopted architecture and assessment process are described below.

The architecture comprises three main components (Fig. 3): (i) a web portal that integrates file

Table 2. Capella radar image metadata

Item	Value
SAR Frequency Band	X
Instruments	capella-radar-3
Datetime	2021-06-12T14:48:43.343984
SAR Instrument	Mode spotlight
SAR Center Frequency	9.65 GHz
SAR Polarizations	HH
SAT	Orbit state: descending
SAR Product Type	GEO
SAR Pixel Spacing Range & Azimuth	0.42 m
SAR Looks Range	1
SAR Looks Azimuth & Equivalent Number	9
SAR Resolution Range	0.5 m
Resolution Ground Range	0.74 m
SAR Resolution Azimuth	0.64 m
Incidence, Look & Squint Angles	41.9°, 38.1°, -0.1°
Orbital Plane	97°
SAR Observation Direction	left
Collect Id	6cf322d2-3935-4803-a587-d8dae7295005
Product Category	custom
Billable Area	25567987.965252765

Source: [7].

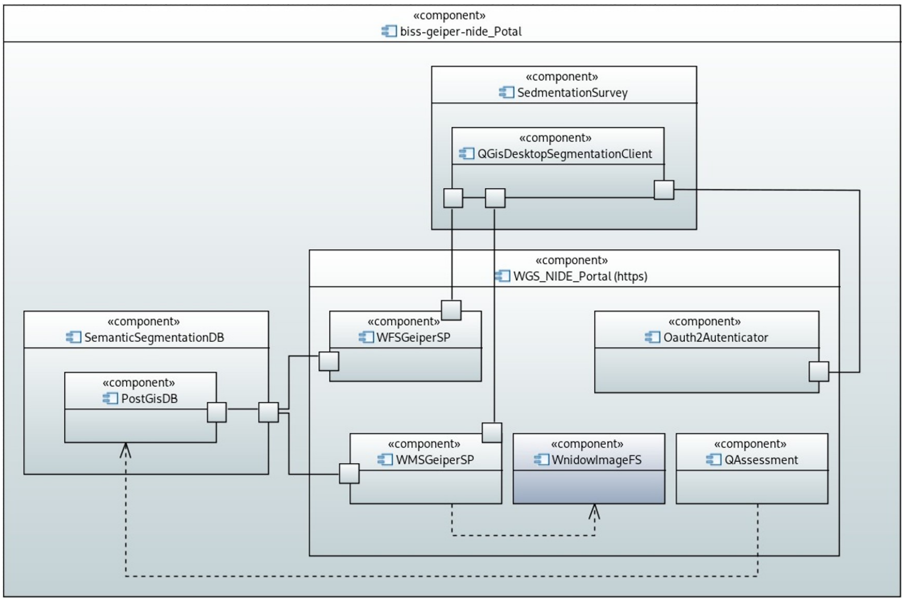

Figure 3. System architecture for accessing and producing reference semantic segmentations through a WFS server. The three main components are the segmentation resources for each user, the web portal that provides the services, and the data repository.

Source: Authors.

storage, Web Map Service (WMS) and Web Feature Service (WFS) servers, and a quality-assessment environment; (ii) a segmentation environment based on the QGIS Desktop client; and (iii) a semantic-segmentation repository implemented in PostgreSQL with the PostGIS extension.

QGIS Desktop client

After a student account has been enabled, the assigned image can be segmented in any client that accesses WMS and WFS servers in accordance with Open Geospatial Consortium standards and supports OAuth 2.0 authentication. QGIS Desktop was selected for the implemented framework (Fig. 3) because it is widely used and meets these requirements.

The student imports an OAuth 2.0 configuration file containing the connection settings for the WMS and WFS servers; alternatively, the connection can be configured manually. Google provides the authentication service through the institutional accounts issued by the university to members of its academic community.

After authentication, the student accesses the assigned Earth-surface image through the WMS server and creates the segmentation through the WFS server. The completed segmentation is returned through the WFS server for storage and subsequent consistency assessment. In the collective knowledge-construction configuration, the WMS server can also display segmentations created by other students assigned to the same image.

Web Geographic Server for NIDE Portal (WSG-NIDE-Portal)

The framework uses HTTPS to protect connection confidentiality through a public–private key pair provided by Universidad Distrital Francisco José de Caldas. The site also uses server-side OAuth 2.0 authentication [8], with Google as the identity provider for institutional accounts through the OAuth2Authenticator component.

Each segmentation layer assigned to a student is provided by the WFS server (WFSGeiperSP), ensuring that only the user with the corresponding credentials can edit it. The WMS server (WMS-GeiperSP) provides the Earth-surface image and the segmentation layers for visualization.

Under the tutor–student approach, each student can access only the assigned image and their own segmentation layer. When collective knowledge construction is enabled, students can also view segmentations created by peers assigned to the same image. In the current implementation, each Earth-surface image is stored in a file system (WindowImageFS) accessible to the website.

Once a segmentation (tutor–student approach) or a set of segmentations (collective approach) is available in the spatial database (SemanticSegmentationDB), the consistency-assessment environment (QAssessment) produces the corresponding quality measures. The tests implement the framework of [4]. In the current version, each assessment is initiated manually in MATLAB through the API associated with that framework.

Semantic Segmentation Database (SemanticSegmentationDB)

Each segmentation is stored in a PostGIS repository (PostGisDB) implemented with the open-source PostgreSQL database management system and its PostGIS extension. Every authorized student has an individual schema for storing their work, while segmentation groups link the outputs of students assigned to the same image. Under the tutor–student approach, the tutor has a separate schema containing the reference segmentation.

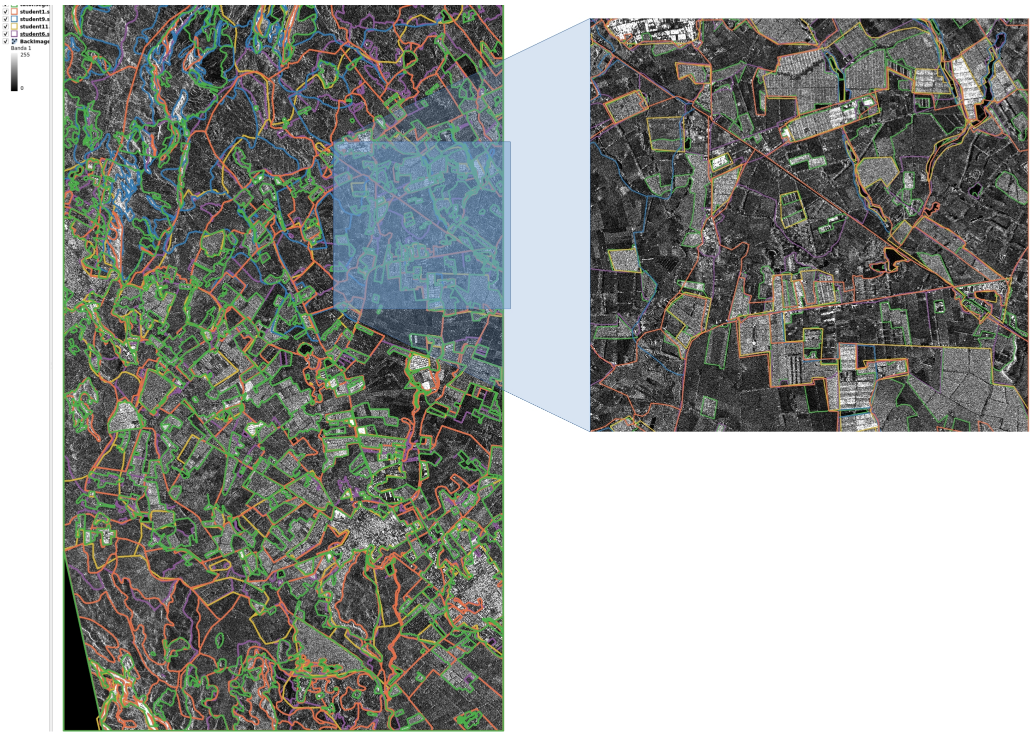

Figure 4. Image and four student-produced segmentations (left) and enlargement of the blue rectangle (right). The reference segmentation is shown in green behind the student outputs.

Source: Authors.

RESULTS

The current implementation was evaluated using both the tutor–student and collective approaches. In the former, consistency measures provide feedback on student performance relative to the tutor's reference segmentation. Figure 4 shows the reference segmentation and four representative student outputs from this experiment.

Figure 4(left) superimposes the four student segmentations on the reference segmentation. Non-green lines indicate boundaries that do not match the reference and therefore reduce precision. In Fig. 4(right), green reference boundaries not covered by a student segmentation correspond to missed boundaries and therefore reduce recall. These patterns are consistent with the quantitative results in Fig. 5. Red points indicate measured performance, whereas the green point marks the ideal location in precision–recall space, which is adopted here for Earth-surface imagery.

Figure 5 shows each student's performance relative to the tutor's reference segmentation, repre-

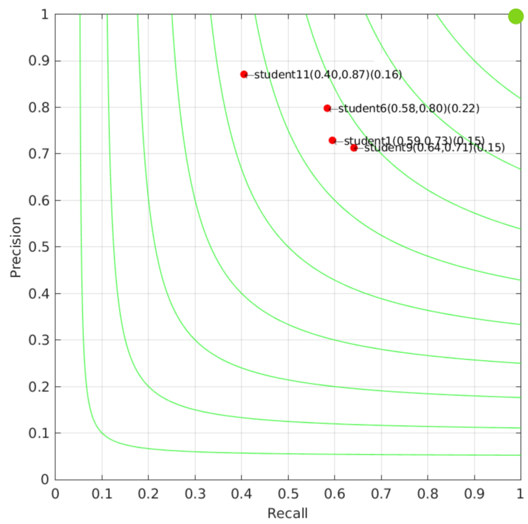

Figure 5. Precision–recall consistency results for four segmentations produced under the tutor–student approach.

Source: Authors.

sented by the bright-green point. Each red point has the same label as the corresponding segmentation in Fig. 4; the first parenthetical values give the recall and precision coordinates, and the second value gives overall thematic consistency. In addition to reporting performance, the method provides a more objective form of feedback than conventional qualitative assessment and helps students identify corrections for subsequent work.

The implementation was also evaluated using the collective knowledge-construction approach, although students could not view their peers' segmentations during the experiments. Two segmentation iterations were completed. Figure 6 shows the source image and the four segmentations produced in the second iteration, which exhibit substantial pairwise similarity.

For each iteration, precision and recall were averaged across all possible pairs of segmentations; the resulting averages are shown as magenta points in Fig. 7. The figure also reports the consistency of each segmentation relative to the remaining outputs (blue or green points in the first iteration and red points in the second). For the second iteration, the precision–recall coordinates appear beside each segmentation label, which corresponds to Fig. 6; the average point is additionally annotated with overall thematic consistency.

The closer the average lies to the upper-right corner of precision–recall space, the greater the

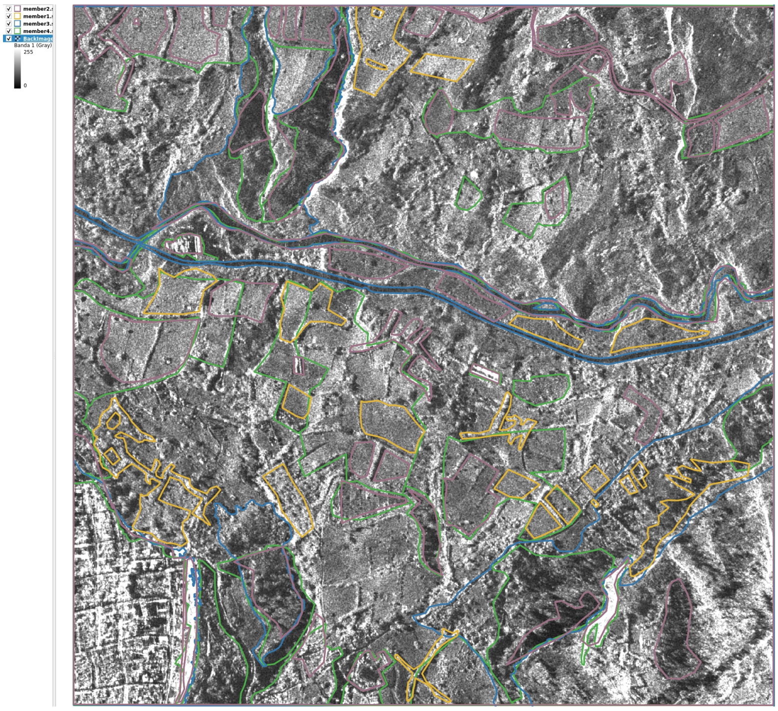

Figure 6. Source image and four segmentations produced in the second iteration of the collective knowledge-construction experiment.

Source: Authors.

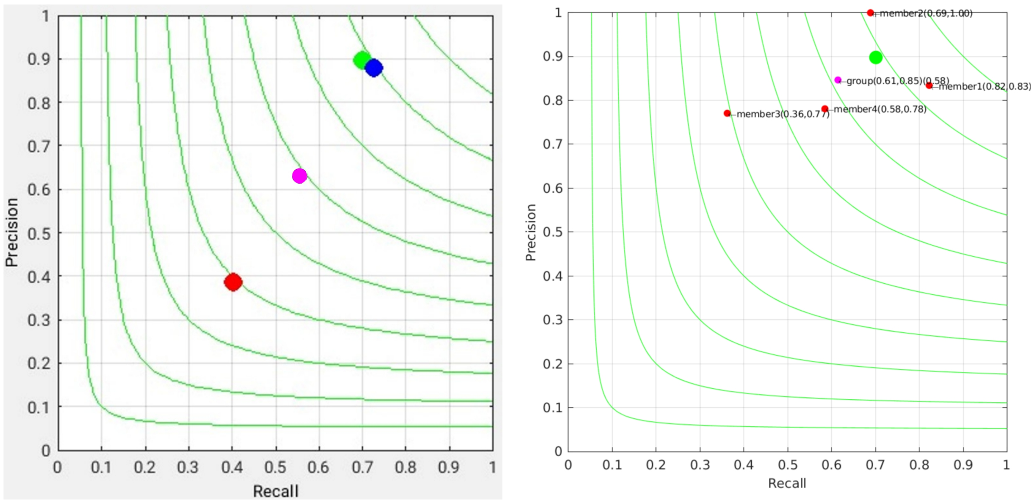

Figure 7. Precision–recall consistency results for four segmentations in the collective knowledge-construction experiment: first iteration (left) and second iteration (right).

Source: Authors.

agreement among the semantic interpretations expressed by the group. As Fig. 7 shows, the group improved its overall precision–recall performance in the second iteration.

Conclusions and future work

This study conducted a series of pilot experiments involving manual segmentation. The variation among segmentations of the same Earth-surface image shows that high internal consistency can be difficult to achieve. Nevertheless, the improvement observed between the two iterations suggests that objective comparative feedback can help students refine their semantic segmentations in subsequent attempts. This iterative process can strengthen both their geographic knowledge of the assigned area and their image-interpretation skills.

In the collective knowledge-construction experiment, the group received its aggregate performance results and reviewed the other segmentations after the first iteration. The second iteration subsequently achieved better performance, as shown in Fig. 7. The increase was more pronounced for precision, although recall also improved.

During each iteration of the collective experiment, students could not view their peers' segmentations while working. Consequently, they could not use those interpretations to adjust their own output or contribute interactively to a shared result. A future experiment will enable this functionality to test whether peer visibility further improves collective consistency.

Precision and recall were calculated in MATLAB using the implementations associated with [1,4]. An adaptation for GNU Octave is under development as a fully open-source alternative.

The experiments yielded relative consistency measures based on each participant's precision and recall, but the number of photointerpreters was small. The resulting set therefore lacks the diversity of independent interpretations assumed in [1, 4]. Although the experiments demonstrate the utility of the computational environment, substantially more photointerpreters are required before the resulting dataset can be considered a reliable ground truth for evaluating semantic-segmentation algorithms.

A major obstacle in semantic-segmentation research is the need for large labeled datasets, whose production by photointerpreters is labor-intensive and costly. For human detection, Shen et al. [9] proposed Progressive Transformation Learning (PTL), in which increasingly realistic transformed virtual images are added gradually to an initial training set. Tian et al. [10] described a method for designing artificial scenes and automatically producing accurately annotated images; their ParallelEye dataset improved model performance when combined with public real-world datasets during training. Applying similar methods to Earth-surface segmentation could reduce the cost of producing labeled data. However, generating realistic Earth-surface imagery remains difficult because scenes contain multiple object classes with diverse geometric and textural characteristics.

The experiments required several segmentation groups to be configured manually, from creating repository schemas to enabling the websites through which datasets were provided. Automating this workflow is therefore an important step toward simplifying and decentralizing system administration.

The experiments used the Radar Systems course as their educational context and the IGAC taxonomy as their semantic classification system. Because both elements are configurable, the framework can be adapted to other Earth-surface semantic-segmentation contexts and extended through additional VLOs.

The datasets, including the images and generated segmentations, are available through the university website at `https://biss-geiper-nide.udistrital.edu.co`. Access to the required WMS, Web Map Tile Service (WMTS), Web Coverage Service (WCS), and WFS endpoints can be requested by emailing geiper@udistrital.edu.co. QGIS Desktop plugins for uploading, downloading, and evaluating semantic segmentations are available upon request through the same address. Ongoing work will extend the platform to manage semantic-segmentation projects in additional geographic areas.

Sponsorship

This work was supported by Universidad Distrital Francisco José de Caldas, Bogotá, Colombia.

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