A GIS-embedded system to support land consolidation plans in Galicia

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Abstract. Land consolidation is a strategic instrument for rural planning and thus economic development in the Spanish region of Galicia. This paper describes an experimental system embedded in a GIS environment to aid rural engineers to develop land consolidation plans. The system supports all the stages of the plan and many functionalities are implemented as heuristic processes based on experts' knowledge and advice. The overall aim is to overcome administrative and technical problems of traditional consolidation procedures. The system provides an integrated framework for the management of spatial and administrative consolidation information. It also includes optimization-based algorithms for the automated generation of multiple alternative parcel reallocations, as well as an environment to refine and objectively evaluate the proposed solutions. These key capabilities result in a powerful tool for decision making that dramatically reduces time and cost of land consolidation plans. Pilot experiences in two consolidation zones of Galicia assess the feasibility and effectiveness of our system.

1. Introduction

Galicia is an autonomous region of Spain located in the north-west of the country (see figure 1), with 29 500 km^2 and a population of almost 3 million

Figure 1: Location map of Galicia and its four provinces.

people. Two thirds of the population live in the countryside in over 30 000 small villages belonging to 3773 parishes of 315 municipalities. A third of the land is dedicated to farmland and the other two thirds of land use are brushland and woodland in approximately the same proportion. The occupation rate of arable land is 20%, showing a decreasing trend.

The large number of scattered settlements, a dominant traditional agricultural economy and a historical tradition of property inheritance by splitting parcels within families, has produced a high degree of parcel subdivision. Thus it is that rural land tenure structure in Galicia is defined by the existence of small holdings (Crecente (1998) reports a mean cadastral parcel of 2500 m^2 and between six and eight parcels per owner), which results in a landscape in the form of a complex mosaic, unlike the rest of Spain. The consequence is that farmers need more parcels to gather enough land to establish a cost-effective and feasible farm, increasing monetary and time costs, as well as generating diseconomies.

Land consolidation has been a policy for dealing with property structure in Galicia since the 1950s, with an investment of more than €30.5 million per year. The basic objective is to reorganize the parcel structure to get larger parcels and a smaller dispersion between the same owner's parcels in order to allow a profitable use of the agrarian and forest properties. Land consolidation is a key action in Galicia for rural development and is understood as a sectorial planning tool that includes the construction of infrastructures. The following statistics reveal the magnitude of the process in Galicia: 312 213 ha of land have been consolidated from 1954 until 1999, involving 289 563 owners and 147 municipalities (765 parishes out of 3773); and consolidation plans have been currently approved in another additional 190 025 ha (Crecente *et al.* 2002).

The great number of consolidation plans, along with the large number of parcels and owners involved in every procedure (Crecente (1998) reports 4000 parcels and 390 owners on average in each consolidation zone), the long duration of the whole process (about seven years), the spatial indefinition of some plans (zones in several parishes and parishes with several zones), and the inexistence of an adequate information support system make land consolidation in Galicia a highly complex spatial planning process.

Different and complementary general-purpose software tools aid experts to solve particular aspects of only some tasks of the process. These tools use different data models and formats. Moreover, the high volume of consolidation information is spread among different institutions and there is a lack of coordination between the participants involved in the process: landowners, rural engineers, local and regional administrations, and consultings. Specific-purpose tools have also been designed to assist the development of consolidation plans, e.g. in The Netherlands (Rosman and Sonnenberg 1998), Hungary (Kovacs 2001), and Morocco (Semlali 2001), but they only cover partial aspects of the consolidation process.

An interdisciplinary research group was formed in 1999 with the goal of developing an integrated system to support the tasks of the whole cycle of the consolidation process in Galicia (Touriño *et al.* 2001). The system was funded by the European Union and the Ministry of Science and Technology, and supported by the Galician Government. The main contributions of our system are summarized in three outstanding aspects:

(a) Development of an information system within a GIS environment, including all the actors and data of the consolidation project during all the stages: from property investigation through project elaboration to property reallocation. It facilitates a direct participation of the owners, the control of the

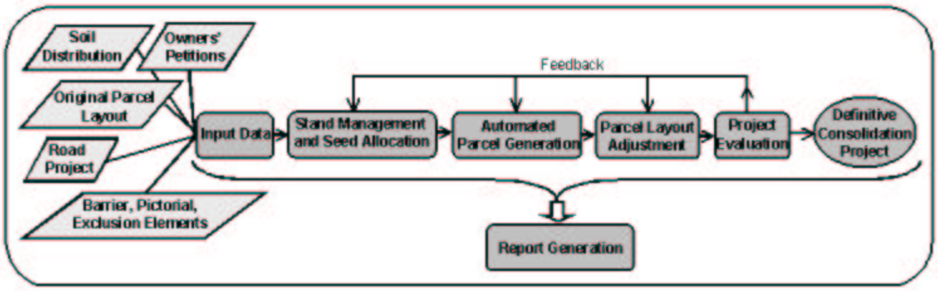


Figure 2: Schematic overview of the land consolidation system.

administration and the validation of the work schedule of the consultancy firm that carries out the project. This feedback system allows a remarkable improvement in quality and duration of the procedure.

(b) Implementation of heuristic algorithms within the GIS to automatically obtain a new structure of the property with a better use of the territory, trying to satisfy all the participating agents and taking into account as many factors that may influence the consolidation process as possible. Our system tries to overcome traditional reallocation strategies by means of an automated approach that generates alternative solutions from different starting points, so that during the process they can evolve into one of the best possible solutions to the consolidation problem.

(c) Evaluation and analysis of the consolidation plan using a set of control parameters to quantify the impact of spatial changes during the whole process, as well as the quality of the obtained solutions. The best solution is thus selected according to the expert's criteria in a feedback process of comparative evaluation.

2. Scope of the consolidation system

We have designed a systematic procedure to approach the elaboration of consolidation projects based on the knowledge and experience of experts, and we have developed our consolidation support system following the stages of the workflow shown in figure 2. The input data consist of different layers of geographical and administrative information of the consolidation zone. The stand management stage splits the consolidation zone into work units (stands) for the planner. Both stages, described in §2.1 and §2.2, respectively, are preliminaries for the next step: the automated parcel generation, described in §3. In this stage, we apply optimization algorithms to each stand in order to obtain a new parcel layout. The parcels of the new layout can be refined manually, as explained in §3.5, to improve the solution. Finally, the project is evaluated using a set of parameters that allow the comparison of different solutions for the same consolidation zone. According to the evaluation results of the project, the engineer can readjust decisions and strategies taken in the previous stages following a feedback process that tries to find the best possible solution. The evaluation stage is further detailed in §4.

The system also provides a set of reports at the different stages to follow the development and progress of the project. Once the project is firm, it also supplies official forms and maps for the different institutions involved in the process: town councils, regional government, cadastre. Selected information is also published on the web for the administrations and the landowners using different access levels. For instance, the owners can make spatial queries about the location and attributes of their new parcels via web so that they can make claims, and the regional government can obtain statistics about the area consolidated in a specific zone.

Regarding implementation details, the system is embedded in Intergraph GeoMedia Professional® and all the new functionalities of figure 2 for the land consolidation process are software components built on top of the GIS and presented as commands through graphical interfaces. The components were developed using ActiveX/COM technology and Visual Basic, except for the algorithm of automated parcel generation, written in C++ due to performance reasons. The GIS technology used was the Geomedia Automation Objects Model. SQL Server is the RDBMS chosen for the management and integration of the input data and the information generated during each stage of the project. The databases reside in a DB server and the system is configured to act as a client in the intranet of the workgroup and provides a collaborative work environment through the sharing of the consolidation information. Spatial information is published on the web using Active Server Pages and Geomedia WebMap® components.

2.1. *Input spatial data*

The first step is to provide the system with georeferenced information about the consolidation zone. The required information to develop the project is obtained in a previous stage of land and property investigation through different means: land surveying, aerial orthophotos, photogrammetry, rural cadastre, personal interviews. We have developed an information system to manage the input data, which consist of the following layers:

- Initial owner and parcel distribution, including administrative information about property registration and land burdens.
- Distribution of soil classes. The soil of the consolidation zone is classified and scored (in points per area unit) by the rural engineers according to the use (irrigated land, dry land, forest), accessibility and productivity (first class, second class ...). So, each parcel is quantitatively scored by intersecting it with the soil layer.
- Exclusion elements. This layer contains geographical entities whose area is excluded from the consolidation process, such as rivers, lakes or areas already consolidated into the boundaries of the target zone.
- Barrier elements. They are entities that, although not excluded from the area to be consolidated, involve constraints on the layout of the new parcels. They include, among others, buildings, irrigation channels, embankments, wells and power lines.
- Pictorial elements. Contour lines, orientation maps and slope maps provide detailed information about the surface for guidance purposes (mainly in the manual layout adjustment described in §3.5), but they do not impose constraints on the automated consolidation procedure.

- The road project for the zone. It involves new constraints on the project elaboration because all the new parcels must join a road in order to be accessible, and there must be a path between any pair of parcels.

- The owners' petitions, which show their preferences on the location of their new parcels. The new parcel distribution must respect these preferences as far as possible to avoid conflicts and dissatisfactions.

2.2. *Stand management and seed allocation*

Consolidation zones are too large to be analysed. Therefore, they are split in subzones named stands to simplify the process. We define a stand as an area of the consolidation zone limited by roads (of the road project) and/or by exclusion elements, and this is the work unit for the planner.

The owners' petitions in each stand are translated into seeds. A seed is a pointer that assigns to an owner a location in the stand as a starting point for the reallocation of a new parcel. Each seed is represented by its location and the score that the associated new parcel should have in the stand. Each owner can have more than one seed in a stand. The goal is to place the seeds as close to the petitions as possible to satisfy the owners. Moreover, a uniform distribution of the seeds is preferred to obtain more regular-shaped parcels. Map information helps to easily detect conflicts in the petitions of different owners.

Our tool aids the engineer to divide the consolidation zone into stands by selecting their boundaries, and to distribute the seeds of the owners by means of a simple interface, as shown in figure 3 for a real consolidation zone, where the stands are numbered and the seeds are represented by points. The tool provides detailed information at seed-level (location, score and owner of each seed), owner-level (number, location and score of his seeds, and score contributed by his parcels), and stand-level (global score of the stand and score of the seeds it contains). The system automatically detects imbalances between the scores of the seeds of each owner and the scores of the parcels contributed by that owner. A thematic map is also provided to classify the state of the stands of the consolidation zone according

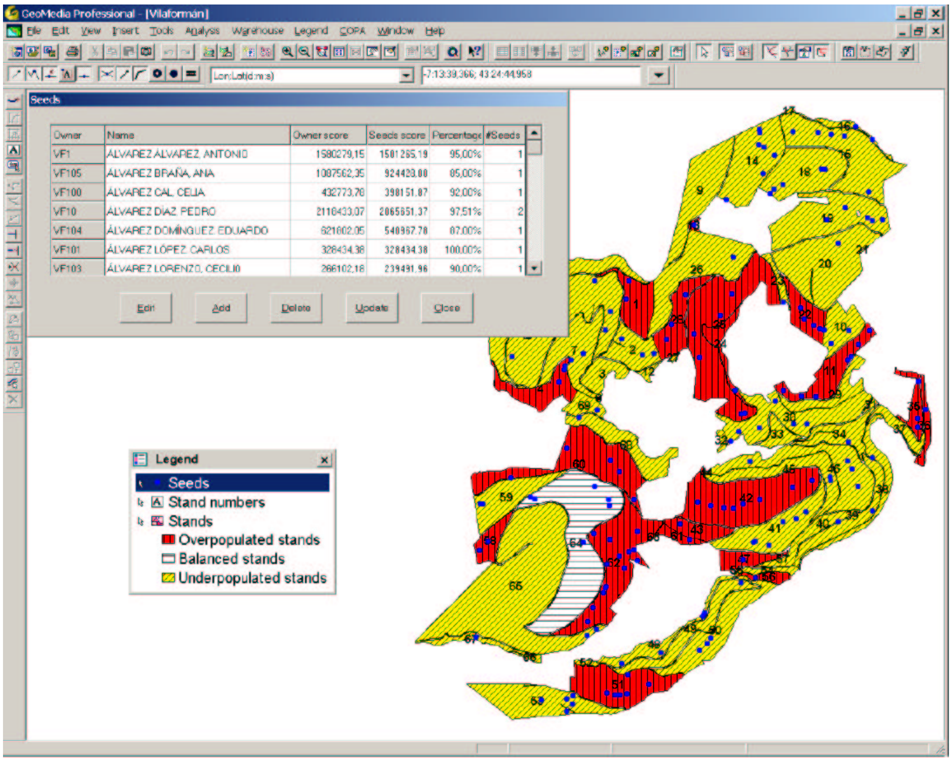


Figure 3: A snapshot of the stand management module.

to the seed distribution (see figure 3): balanced (the sum of the scores of the seeds in the stand is similar to the global score contributed by the stand), overpopulated (the sum is higher), or underpopulated (the sum is lower). In the last two cases, the planner must readjust the score and/or the location of the seeds to balance the stand.

Once the stands are balanced, the seeds provide a distribution of the starting locations of the new parcels, as input for the next stage, the automated parcel generation, which works at stand-level.

3. Automated parcel generation

Rural engineers have traditionally used non-automated techniques to partition the stand. They plot the new parcels independently, one after the other, beginning at one extreme of the stand and finishing when all the area of the stand is assigned, in a tedious manual trial-and-error procedure guided by experience and intuition.

The stand partitioning can be approached as an optimization problem (Jain *et al.* 1999). In our proposal, the objective function to be optimized represents the quality of both the individual parcels and the stand partition as a whole by taking into account the relationships among parcels. Thus, heuristic techniques can be applied to find an extreme value of the function which corresponds to an optimal or near-optimal partition of the stand. This partition must fulfil the constraints and requirements of the consolidation project.

We used the simulated annealing method (Kirkpatrick 1984) to guide the search for feasible solutions. As the method closely depends on the initial partition, an appropriate one is generated, as described in §3.2 and §3.3 and then, the final solution is calculated through simulated annealing in an iterative refinement process (§3.4) and a further manual adjustment embedded in the GIS environment (§3.5).

3.1. *Mesh construction*

The first step is to convert the vector geometries of the stand into a two-dimensional mesh of discrete elements named cells. Each cell is weighted by intersecting the mesh with the stand layout and the layer of soil classes. The orientation angle of the mesh, the cell shape and the area represented by each cell is selected by the engineer. The area is a tradeoff between computational and memory overhead of the automated parcel generation and the accuracy of the results. This stage requires long computation times, but the mesh can be stored and reused if necessary.

The problem of geometric partition is then transformed into a discrete problem of distribution of a set of cells in as many subsets as new parcels must be generated. As the mesh structure can be considered as an adjacency graph, graph theory is applied to solve some steps of our algorithm.

Each stand is represented as a set of cells $V = \{e_i\}$, $1 \leq i \leq \|V\|$. Each cell e_i is characterized by the pair $[(x_i, y_i), z_i]$, where (x_i, y_i) are the cell coordinates in the mesh, and z_i is the cell weight or score, given by the size and the soil class of the cell. The score of the mesh is $Z = \sum_{i=1}^{\|V\|} z_i$.

Definition 1. Two cells e_i and e_j $(i \neq j)$ of V are neighbours if $|x_i - x_j| \leq 1$ and $|y_i - y_j| \leq 1$.

The mesh must be connected, i.e. there must exist a path between any pair of cells of V across neighbouring cells.

Definition 2. We define a P-partition of mesh V, U, as any set of P disjoint subsets of mesh cells, u_j, named domains:

$$U = \{u_j\} \text{ such that } V = \bigcup_{j=1}^{P} u_j, \text{ and } u_j \cap u_k = \emptyset, \forall j \neq k, 1 \leq j, k \leq P \qquad (1)$$

and each cell $e_i \in u_j$ is assigned a new parameter p_i that represents its owner.

Our problem is then formulated as follows: given the initial partition of V in M domains (the original parcel layout is an M-partition), $U^{init} = \{u_j^{init}\}$, assigned to N owners $(M \geq N)$, our goal is to obtain a new N-partition U of V (one domain per owner) so that:

- Each owner n, $1 \leq n \leq N$ keeps in the new partition the contributed score within a fixed tolerance range ϵ_n:

$$\left(\sum_{e_i \in V/p_i^{init}=n} z_i \right) - \epsilon_n \leq \sum_{e_i \in V/p_i=n} z_i \leq \left(\sum_{e_i \in V/p_i^{init}=n} z_i \right) + \epsilon_n \qquad (2)$$

- The new partition minimizes a certain cost function:

$$\mathcal{F}(U) = \min\{\mathcal{F}(U^j)\} \qquad \forall\ N\text{-partition } U^j \text{ of } V \qquad (3)$$

According to our specifications, the search of the optimal partition is an NP-complete problem and therefore heuristic methods are applied to find near-optimal solutions at a computational cost proportional to the problem size.

3.2. *Domain growth stage*

We propose an iterative seeded growing method to obtain an initial distribution of the domains by means of a heuristic flooding process for region growing and competition. Similar methods can be found in the literature (e.g. Najman and Schmitt 1996, Zhu and Yuille 1996, Grzeszczuk and Levin 1997, Herman and Carvalho 2001). First, we introduce some concepts that will be used in this stage.

Definition 3. We define the global stand centre, e^c, of a mesh V as:

$$e^c = (x^c, y^c) = \left(\sum_{e_j \in V} \frac{x_j}{\|V\|}, \sum_{e_j \in V} \frac{y_j}{\|V\|} \right) \tag{4}$$

Definition 4. The following distance functions between two cells e_i and e_j (namely, D_e, D_s and D_m, and generally referred as D) are defined to quantify the proximity between mesh cells:

$$D_e(e_i, e_j) = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} / S_e \tag{5}$$

$$D_s(e_i, e_j) = ((x_i - x_j)^2 + (y_i - y_j)^2) / S_s \tag{6}$$

$$D_m(e_i, e_j) = (|x_i - x_j| + |y_i - y_j|) / S_m \tag{7}$$

S_e, S_s and S_m being the rescaling constants to guarantee $0 \leq D \leq 2$:

$$S_e = \sqrt{(\frac{1}{2}(x^{\max} - x^{\min}))^2 + (\frac{1}{2}(y^{\max} - y^{\min}))^2} \tag{8}$$

$$S_s = (\frac{1}{2}(x^{\max} - x^{\min}))^2 + (\frac{1}{2}(y^{\max} - y^{\min}))^2 \tag{9}$$

$$S_m = \frac{1}{2}(x^{\max} - x^{\min}) + \frac{1}{2}(y^{\max} - y^{\min}) \tag{10}$$

$$\text{where} \quad x^{\max/\min} = \max_{1 \leq i \leq \|V\|} / \min(\{x_i\}) \qquad y^{\max/\min} = \max_{1 \leq i \leq \|V\|} / \min(\{y_i\})$$

The three distance functions are norms. As all norms on a finite-dimensional vector space are equivalent, they can be indistinctly used in our method to compare distances, although D_s and D_m are less costly to compute.

Next, we detail the steps followed by the domain growth process. Initially, each domain is composed of only one cell, $e_n^s = (x_n^s, y_n^s)$, which corresponds to the owner's seed fixed in the previous stage (see §2.2):

$$u_n = \{e_n^s\}, \ 1 \leq n \leq N \tag{11}$$

Definition 5. The useful neighbourhood of a subset of cells $u \subset V$ is another subset of V (candidate cells), w, that fulfils:

$$w = \{e_i \in V / e_i \notin u_n \forall n, 1 \leq n \leq N, \text{ and } \exists e_j \in u,$$

$$\text{such that } e_i \text{ and } e_j \text{ are neighbours}\} \tag{12}$$

At every iteration of the growth of domain u_n, each cell e_i of its useful neighbourhood w_n is assigned a value that quantifies the adequacy of the inclusion of e_i in u_n, and then the most adequate cell from w_n is selected. The heuristic function that we propose to evaluate the adequacy of each cell is given by a linear combination of the following terms:

$$F^n(i) = \sum_{j=1}^{6} \alpha_j f_j^n(i) \tag{13}$$

- The first term focuses on the distance to the stand centre (see equations (4) to (10)) and represents the tendency to grow towards the external boundaries of the stand.

$$f_1^n(i) = D(e_i, e^c) \tag{14}$$

- The second term gives priority to the proximity to the seed of the corresponding owner, and shows the tendency to grow in the neighbourhood of the seeds.

$$f_2^n(i) = 1 - D(e_i, e_n^s) \tag{15}$$

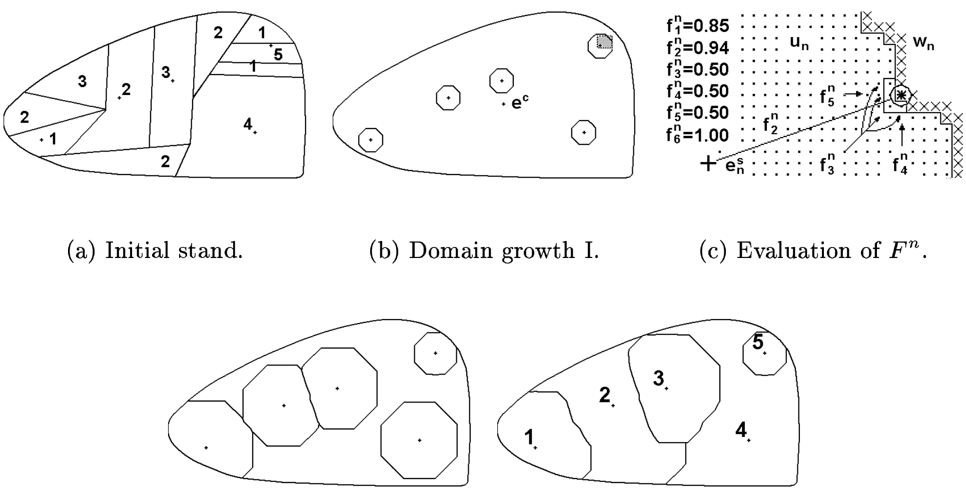
- The third factor favours those cells with a greater number of neighbours, which results in more regular parcels.

$$f_3^n(i) = \frac{1}{8} \|\{e_j \in u_n / e_i \text{ and } e_j \text{ are neighbours}\}\| \tag{16}$$

- The fourth and fifth terms force the domains to follow a vertical or a horizontal orientation in the mesh, respectively. They are useful to fit the shape of the parcels to the mesh orientation when the planner determines the distribution that takes the best advantage of the terrain configuration.

$$f_4^n(i) = \frac{1}{2} \|\{e_j \in u_n / x_i = x_j \text{ and } |y_i - y_j| = 1\}\| \tag{17}$$

$$f_5^n(i) = \frac{1}{2} \|\{e_j \in u_n / y_i = y_j \text{ and } |x_i - x_j| = 1\}\| \tag{18}$$



(a) Initial stand. (b) Domain growth I. (c) Evaluation of F^n.

(d) Domain growth II. (e) New partition.

Figure 4: Example of the domain growth process.

- The last term gives priority to the growth over existing parcels of the initial layout, U^{init}, if the engineer considers that the disposition of the original parcels was well adapted to the characteristics of the terrain.

$$f_6^n(i) = \begin{cases} 1 & \text{if } \exists e_j \in u_n / p_i^{init} = p_j^{init} \\ 0 & \text{otherwise} \end{cases} \tag{19}$$

The planner guides the process by weighting the importance of each term through the α_j coefficients of equation (13), according to his criteria. Thus, a wide variety of alternative solutions may be obtained until the preferences of the expert are satisfied. The domain growth strategy can also be selected. In the round robin strategy each owner selects only one cell per iteration in consecutive order. In the 'full-owner' strategy the whole domain of each owner is generated by turns, one after the other. The growth process ends when the score of the domain of every owner fulfils equation (2).

The growth of the domains from the initial seeds (represented by points) is depicted in figure 4. The first picture of the figure shows the initial stand that consists of eleven parcels (M=11) and five owners (N=5). The stand is divided

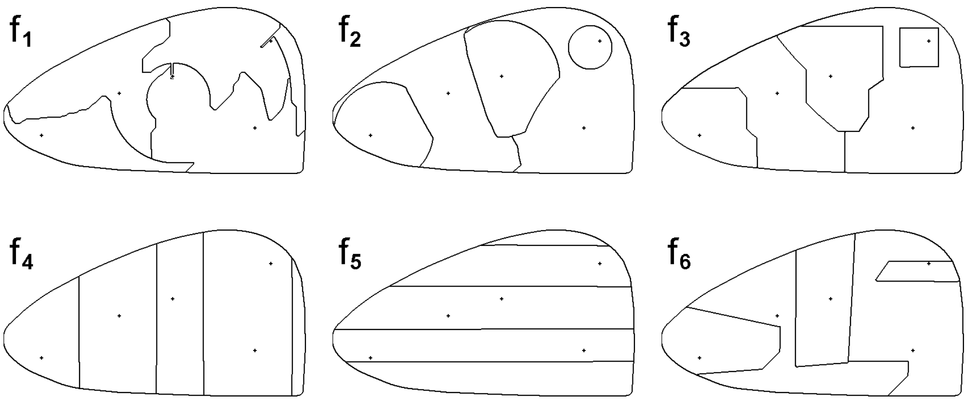
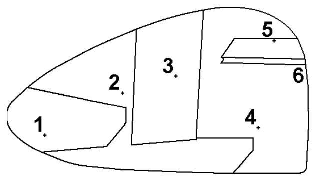


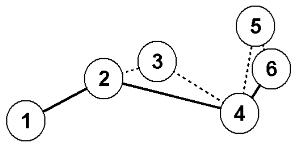
Figure 5: Alternative solutions in the domain growth stage.

into square cells of 1m × 1m and the orientation angle of the mesh is 0^o. Only the coefficients α_1, α_2 and α_3 are active (with the same weight). The growth strategy employed was round robin. Figure 4(c) zooms in on the shaded area of the domain of figure 4(b). It shows the evaluation of the heuristic function $F^n(i)$ of equation (13) for a cell (indicated as $*$) in w_n to select the best cell from this set. For illustrative purposes, figure 5 shows different 'extreme' solutions after the growth process by stressing only each one of the terms described in equations (14) to (19). Note that the partition of the last picture (f_6) follows the disposition of the initial stand (figure 4(a))

3.3. *Domain merge*

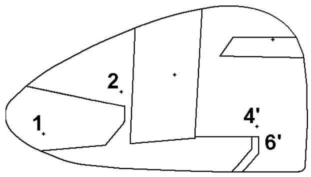
During the growth process of the previous stage, it is possible that $w_n = \emptyset$ (there are no candidate cells). Therefore, a new growing domain (secondary domain) must be created and assigned to the owner starting from a non-assigned cell as close to the seed as possible. In this situation, illustrated in the first picture of figure 6, one owner may have two or more disconnected domains in the stand. The aim of the merge stage is to group them in only one domain around the primary domain. The problem is approached by means of graph theory. We build an adjacency graph so that each node represents one domain obtained in the growth stage, and the edges define neighbourhood relationships between domains. A shortest

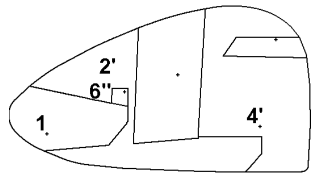


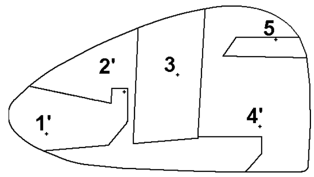


(a) Disconnected domains (1 and 6).

(b) Adjacency graph.







(c) Merging 4 and 6.

(d) Merging 2 and 6.

(e) 1 and 6 merged.

Figure 6: Example of domain merge stage.

path method (Chandy and Misra 1982) was used to transfer the ownership of the cells (and, therefore, their score) from the source node (secondary domain) to the destination node (primary domain), traversing all the intermediate nodes of the path.

Figure 6 shows an example of the process. There is one owner with two disconnected domains (numbered as 1 and 6). This situation was obtained by applying to the initial stand in figure 4(a) the full-owner strategy and weighting it only with α_6. In order to group those domains, an adjacency graph is built (figure 6(b)) and the shortest path between domains 6 and 1 is calculated (6→4→2→1). Domains 4 and 6 are joined and then split (4' and 6') along the 2–4 border to effectively approximate domain 6 (now 6') to domain 2. The process is repeated until domains 1 and 6 are merged, as shown in figure 6(e).

3.4. *Iterative refinement*

As stated before, simulated annealing (Kirkpatrick 1984) is applied to the partition obtained in the previous stages, as basic strategy to minimize the objective function that characterizes the quality of the partition. The shape and size of the parcels are weighted in this function so that the most suitable parcel layouts correspond to minima of the function. We propose as cost function G the following sum of two terms for each owner n of domain u_n:

- One term to make regular the shape of the domain:

$$g_1^n(u_n) = \left| \frac{1}{16} - \frac{\text{area}(u_n)}{\text{perimeter}^2(u_n)} \right| \tag{20}$$

  This function has a minimum (null) for square shapes and it rises as the domain shows an irregular form.

- The second term is a constraint that forces every owner n to keep the contributed score z^n in the partition:

$$g_2^n(u_n) = \left| z^n - \sum_{e_i \in u_n} z_i \right| \tag{21}$$

In the simulated annealing process, the iterative refinement is performed through a series of small stochastic modifications to the domain boundaries. The modifications (or moves) are directed so that their successive application leads to an improvement of the shape of each domain and hence the global solution. The choice of the trial moves and the mechanism that determines whether a move is accepted or not are two important factors in the process. We consider two modifications in our context: reassignment of a border cell of a domain to the corresponding neighbouring domain, and interchange of a pair of border cells between two neighbouring domains. In both cases, the domains and cells involved are randomly selected.

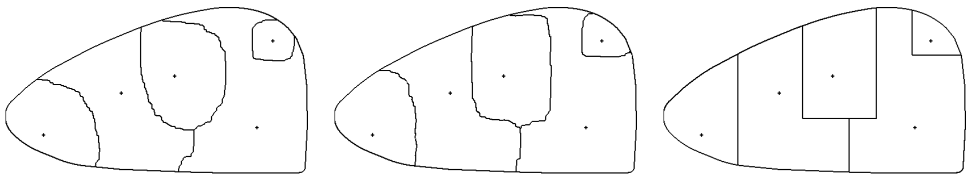
The basic parameter that controls the acceptance process in the simulated annealing is the temperature (Kirkpatrick 1984). It sets the probability of acceptance of a modification according to the Boltzmann distribution; the higher the temperature is, the greater the probability is. The algorithm is characterized by a high initial temperature, a lower final temperature and a cooling schedule that determines the intermediate temperatures between both extremes. The algorithm lies in a geometric cooling process that modifies the initial partition at high temperature. The layout solution is obtained at temperature zero, ideally.

The annealing evolves so that at each temperature of the schedule a thermal equilibrium is achieved, i.e. the solution computed up to this moment is the best minimum that can be obtained at that specific temperature. As a consequence, each temperature of the schedule is used as an accuracy threshold that divides the algorithm into a set of stages. In each stage of the cooling process, the acceptance of a certain number of moves is checked with the aim of achieving the equilibrium condition. The number of moves must be enough to explore a reasonable solution space and, in our approach, it is proportional to the number of border cells between domains. In order to improve the algorithm, instead of allowing the solution to smoothly tend to the thermal equilibrium, a stage is forced to end when a threshold number of moves are accepted. Therefore, computation time is reduced without losing accuracy in the results.

In our scope, as only two domains are involved in each modification, the cost function G (see equations (20) and (21)) is evaluated only for the two domains in an independent way in order to check the acceptance condition (unlike the classical implementations of annealing, where all the domains would be evaluated as a whole). If the modification is not accepted by one domain then the move is rejected. Using this approach of independent optimizations, the contribution of an individual move to the global minimization process is balanced, as it does not take into account the size of the domains modified by the move.

The iterative refinement ends after a fixed number of stages, which is a tradeoff between computation time and quality of the final solution. Figure 7 shows the temporal evolution of the annealing algorithm for a cooling schedule that determines 10 000 stages. The starting partition is the one obtained after the domain growth stage (figure 4(e)).

Finally, the new parcel layout is converted into vector geometries to be manipulated by other modules of the system such as the parcel adjustment tool.



(a) After 100 stages. (b) After 1000 stages. (c) After 10 000 stages.

Figure 7: Example of refinement by simulated annealing.

3.5. *Interactive parcel layout adjustment*

Some parcels generated by our algorithm as an initial solution of the consolidation project may have an unsuitable shape and size according to the planner's viewpoint. Moreover, sometimes it is necessary to change the boundaries of a parcel to fulfil a specific constraint not dealt by the algorithm. The system provides an editing tool to interactively adjust the boundaries of the parcels by moving, adding or deleting vertices. The tool is guided by the engineer's experience to improve the layout, and the layers of barrier and pictorial elements can be used as templates to do this task. The tool shows, through several parameters, how the changes in the boundaries affect the edited parcel and its neighbouring parcels. These parameters are area, perimeter and score of the involved parcels (detached for each soil class), score of the corresponding owners, as well as parcel-level geometric indicators to evaluate the changes (e.g. the ratio area/perimeter). According to the parameters (further described in the next section), the engineer can confirm or undo the changes in a feedback refinement process. Figure 8 shows a snapshot of the editing environment, where the window at top left provides dynamic information about the parcel being edited, and the other two windows display the parameters of the neighbouring parcels (identified by different colours).

4. Evaluation of the consolidation project

The automated partitioning generates a wide set of alternative solutions due to the great variety of input parameter combinations. It is then essential to have an

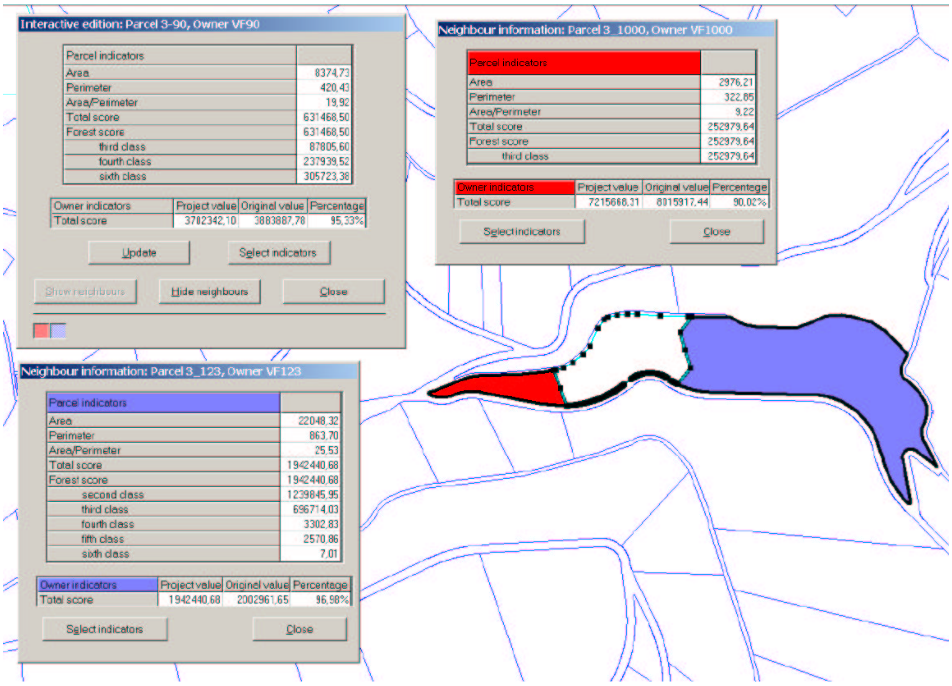


Figure 8: Example of interactive parcel adjustment.

evaluation module that allows, on the one hand, the guidance of the consolidation process towards the search of the best possible solution and, on the other hand, the validation of the final solution as compared to the original parcel layout. Van Huylenbroeck *et al.* (1996) and Coelho *et al.* (2001) propose a multidisciplinary approach to evaluate land consolidation projects, including economic, environmental and social effects. They also outline a comparison of model predictions (*ex-ante* evaluation) with observations after the implementation of the land consolidation project (*ex-post* evaluation). The limitation of their analysis lies in the fact that they do not use GIS support and thus their models are only applied to specific cases where information is managed manually.

A complete set of statistics and parameters are provided by the system to characterize the consolidation project. These indicators also allow the engineer to establish objective criteria to compare different solutions to the same project. They are obtained using spatial operations and geometric calculations embedded in the GIS. Some indicators can be applied at different stages of the project and at different levels: from an individual parcel to an owner or a stand, or even to the whole consolidation zone.

There are classical indicators that evaluate the consolidation process by comparing the initial layout and the final solution. The most outstanding indicators are the consolidation coefficient (CC) and the reduction coefficient (RC):

$$CC = \frac{p_b}{p_a} \qquad\qquad RC = \frac{p_b - p_a}{p_b - ow} \times 100 \tag{22}$$

where p_b, p_a are the number of parcels before and after the consolidation, respectively, and ow is the number of owners of the consolidation zone. The maximum achievable RC is 100%. These indicators only provide a vague and partial evaluation of the process. Therefore, they are complemented in our system by a set of additional morphological and dispersion indicators that improve the decision-making process (González 2002).

4.1. *Morphological indicators*

They assess if an appreciable improvement took place in the shape and size of the new parcels. The larger area of the new parcels usually results in an increase of productivity and the shape of the new parcels may favour agronomic exploitation. Besides the area of the parcels, the following morphological indicators provide useful information to the planner:

- The perimeter of the parcel has a great agroforestry significance because it is directly related to some costs associated with the economic exploitation of the parcel, e.g. mechanization costs or construction of a perimeter fence.
- Profitability. It is the ratio area/perimeter and quantifies the geometry of the parcels. It is useful when they have an agronomic or forest use.
- The relative profitability, given by the ratio area/(perimeter)^2, is another reliable indicator of the parcel shape. As it is a dimensionless parameter, the parcels can be morphologically characterized independently of their area.

The influence of size, shape and distribution of parcels on agricultural productivity is further discussed by Van Dijk (2000).

4.2. *Dispersion indicators*

These parameters quantify the dispersion of the parcels of each owner in the consolidation zone. It is expected that after the consolidation the new parcels of the same owner are closer, which improves their agricultural and forest use. The most representative dispersion indicators of our system are:

- Centroid dispersion. The centroid of a parcel is the average sum of the coordinate points that delimit the parcel. The centre of gravity of an owner is the average of the centroids of his parcels in the consolidation zone. The centroid dispersion indicator of an owner is then calculated as the sum of distances between his centre of gravity and the centroid of each one of his parcels.

  A variant of this parameter, the petition adjustment indicator, quantifies the dispersion of the new parcels of each owner with respect to his petitions at the beginning of the project. It is basically the sum of distances between the centroid of the parcel and the coordinate of the petition. This indicator represents the satisfaction level of the owner.

- Weighted centroid dispersion. It is like the indicator of centroid dispersion, but distance is weighted with the score of the parcel. The reason is that distance is a more critical factor for productive parcels than for parcels with soil of low quality and/or with small area, which are not usually exploited.

- Hamiltonian circuit. This indicator measures the distance of a Hamiltonian circuit that traverses all the parcels of a same owner. The circuit starts from the centre of gravity of the owner, continues with the closest parcel to the centre, next with the closest parcel to the previous one and so on, until the circuit is completed at the initial point, after traversing all the parcels of the owner.

5. Pilot results

Our system was tested in a set of pilot consolidation zones, covering all the stages of the process. In this section we present the results of two pilot zones, Vilapena and Vilaforman, two parishes located in the municipality of Trabada, north-east of the Galician province of Lugo (see map of figure 1). The consolidation zone of Vilapena has 70 ha and consists of 1053 parcels that belong to 94 owners. The average area per parcel is 0.066 ha. The consolidation committee fixed sixteen soil classes for this zone, which is basically of agricultural use. Regarding Vilaforman (specifically, the forest zone of the parish), it is a larger consolidation zone of 650 ha, 2393 parcels, 204 owners and an average area per parcel of 0.272 ha. Among the nine soil classes identified in Vilaforman, the six kinds of forest are predominant (80%).

We had many difficulties in gathering cartographic information of the zones in GIS format. A lot of effort was devoted to the preparation and normalization of the existing layers of information according to our database design. Regarding administrative information, it was obtained from different sources (mainly cadastre and regional government). Some information was duplicated in both institutions and, surprisingly, out of date in many cases. Much time was spent on checking data correctness. In this sense, the data model of our system also provides a framework for the validation and normalization of the consolidation information, as well as for the coordination of the institutions involved in the process, which requires decisions and commitments at political level.

Once the data collection phase was completed, the stand management module helped us to split Vilapena and Vilaforman in 21 and 67 stands, respectively, as well as to organize the owners' petitions and the seeds for the reallocation process. Some petitions were not reasonable; for instance, some owners ask for parcels with a certain soil class and none of their parcels contribute that class to the consolidation. These situations are graphically shown to the owners on the map with the support of quantitative parameters provided by the system. This interaction in the early stages of the project avoids future objections to and claims against the consolidation plan. Besides the petitions, the layer of barrier elements was useful for the seed allocation; for example, the location of the house of an owner was considered as a fixed seed.

Once the seeds were located so that the stands were balanced, the strategy followed by the planner was to approach the automated reallocation from the most difficult-to-solve stand (according to his criterion) to the easiest-to-solve stand. We converted each stand into a mesh of 1 m^2 cells for the automated parcel generation process. Although various parameter combinations were tried, the main strategy employed was to prioritize the generation of the new parcels over existing parcels of the initial stand. As a result, the new parcels were strongly influenced by the shape and the spatial arrangement of the original parcels.

The automated reallocation achieved moderate but encouraging results. It is clear that for simplicity reasons the reallocation algorithm cannot take into account all the factors of the process such as, for instance, the barrier and pictorial elements mentioned in §2.1. Nevertheless, it gave to the engineers good starting points for a further intensive process of layout refinement with the aid of the interactive editing tool.

Our GIS-embedded evaluation module provided a complete set of parameters for the new parcels, owners, stands and the whole consolidation areas. It was also used in intermediate stages of the project to provide feedback on the terms of the heuristic function used in the automated reallocation, in order to improve those indicators considered significant by the planner in these particular zones. Figure 9 depicts the original parcel layout of Vilaforman (left) and the new parcel distribution at the end of the project (right).

After the reallocation process, we obtained similar consolidation and reduction coefficients for both pilot zones (see equation (22)): CC=4.94 and 5.03 for Vilapena and Vilaforman, respectively (i.e. the number of parcels was reduced approximately to a fifth), and RC=87.6% for the two zones, which is a significant reduction. As the classical indicators are not enough to evaluate the plans properly, tables 1 and 2 show various morphological and dispersion indicators for each

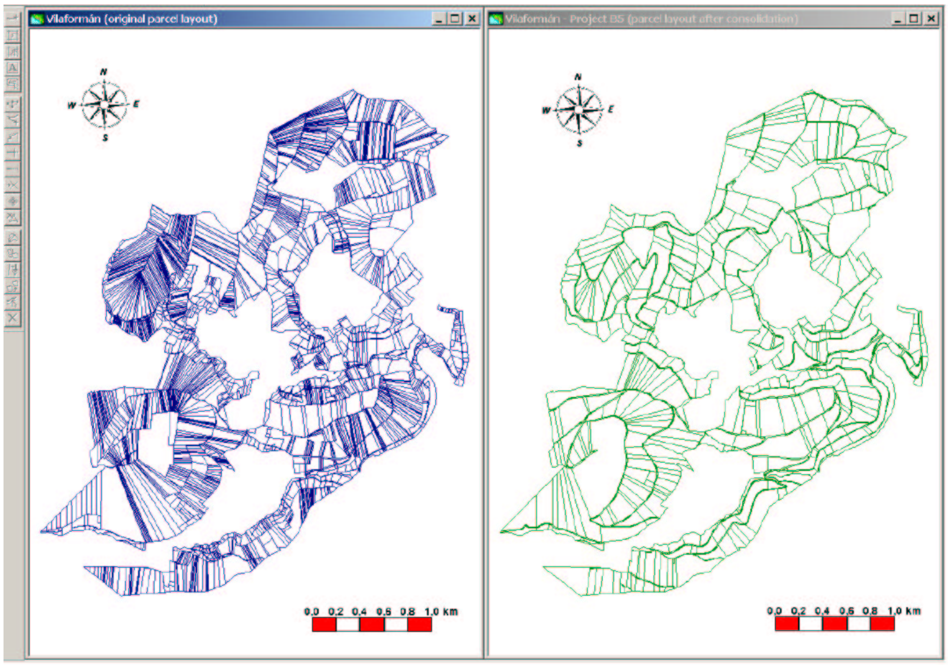


Figure 9: Pilot zone (Vilaforman) before and after the consolidation process.

pilot zone, both a global evaluation of the consolidation zone and an owner-level evaluation. The rightmost column is the percentage of improvement in the indicators with respect to the values of the initial layout. As can be observed in the tables, the morphological indicators show a noticeable improvement in the area, perimeter and shape (given by the profitability) of the new parcels. The average parcel area in the new layout of Vilapena is 0.329 ha, and 1.366 ha in Vilaforman. The grouping of the properties of each owner is clearly reflected in the dispersion indicators (see, for instance, the Hamiltonian circuit), resulting in a reduction in travel times and an increase in work effectiveness.

In general, the morphological indicators are better in Vilaforman due to the starting situation: an average parcel area four times larger than in Vilapena. But the dispersion indicators are better in Vilapena because the consolidation area is much smaller, which facilitates the grouping of parcels to reduce distances. Nevertheless, although Vilapena and Vilaforman present different starting parameters and characteristics (e.g. agricultural vs forest use), the magnitude of the

Table 1: Vilapena zone: evaluation indicators before and after the consolidation.

Vilapena	Consolidation zone		Average per owner		%Improv.
	Before	After	Before	After	
Number of parcels	1053	213	10.9	2.3	79%
Parcel perimeter	121.9km	52.0km	1.3km	0.6km	57%
Profitability	476	984	4.9	10.5	107%
Relative profitability	4.2	4.6	0.0433	0.0488	13%
Centroid dispersion	316.6km	44.0km	3.3km	0.5km	86%
Weighted centroid disp.	184×10^8	137×10^8	1.90×10^8	1.45×10^8	24%
Hamiltonian circuit	278.1km	66.5km	2.9km	0.7km	76%

Table 2: Vilaforman zone: evaluation indicators before and after the consolidation.

Vilaforman	Consolidation zone		Average per owner		%Improv.
	Before	After	Before	After	
Number of parcels	2393	476	11.8	2.3	80%
Parcel perimeter	737.7km	267.2km	3.6km	1.3km	64%
Profitability	1688	4221	8.3	20.7	150%
Relative profitability	6.4	8.2	0.0315	0.0403	28%
Centroid dispersion	1788.6km	221.9km	8.8km	1.1km	88%
Weighted centroid disp.	355×10^9	261×10^9	1.75×10^9	1.28×10^9	27%
Hamiltonian circuit	1106.0km	260.5km	5.4km	1.3km	76%

improvement in each indicator is very similar in the two zones.

6. Conclusions

The system presented in this paper provides a useful support for spatial planning and decision making in a GIS environment. It facilitates the normalization and management of consolidation data in an integrated framework, the automated generation of alternative plans and the comprehensive evaluation of the solutions. From a social point of view, it makes land consolidation more transparent to all the agents involved in the process, improves their cooperation and allows the direct participation of landowners in the different consolidation stages to avoid dissatisfaction and complaints, which results in cost and time saving. In fact, the reallocation time is dramatically reduced from several months to several weeks. Although the system takes into account most of the project's requirements, it is clear that not all the factors of the consolidation project can be quantified, so that the rural engineer must guide the process and take the final decisions on the basis of his experience and the information available to him.

The outcomes of the pilot experiences have been encouraging and the research and development work is to continue. The two main research lines are, on the one hand, the study and implementation of new evaluation parameters and statistics; for instance, specific indicators for zones of agricultural use that take into account the kinds of crops (Sky 1995), and socioeconomic parameters. On the other hand, the improvement of the heuristic function for the automated reallocation by including new factors that may influence the consolidation process.

In a further step, our aim is the introduction of the system in the regional administration. As it is a complex system and land consolidation is subject to many legal regulations, the implantation involves a great effort to reorganize and restructure traditional consolidation procedures, but the potential benefits overcome these drawbacks. The institutional involvement and commitment will play a key role in its success. Finally, the experiences gained suggest that several functionalities of the system might be adopted in other kinds of territorial processes, such as urban planning or shellfishing plans.

Acknowledgements

This work was carried out in the framework of the project 'Design of a GIS application to generate land consolidation plans', co-funded by the European Union and the Spanish Ministry of Science and Technology under Contract 1FD97–2415–C03. We also acknowledge the support of the Department of Agrarian Structures of the Galician Regional Government, responsible for the land consolidation process in Galicia, and Eido Galicia Consulting for contributing years of professional expe-

rience in consolidation projects.

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