Use of geographic information systems in (planning) sustainable land management in Brazil: potentialities and user needs

Antônio Ramalho-Filho[1], Ronaldo Pereira de Oliveira[1] and Lauro Charlet Pereira[1]

ABSTRACT

Some research agendas require knowledge on potentialities of natural resources and socio-economic context in order to supply meaningful information for sustainable development. However, strong limitations hinder integration and interpretation of such data. The objectives of this study were to: (1) determine the land natural potential for agriculture in Brazil by physiographic region, (2) establish a stratification of land potential according to land management levels, and (3) develop a system analysis that offers both management of attributes and simulation of scenarios. The methodology was based on different levels of abstraction, *eg*, quantitative modelling of natural phenomena for land suitability and availability in Brazil; conceptual modelling of terrain objects; and software engineering modelling to supply user demands. The partial results include stratification of land use potentialities according to management technologic levels. The area distribution by crop production suitability suggests that management with adoption of technology plays an important role for increasing agricultural production. The conclusions are that: (1) Brazil has an enormous potential for agriculture, in which opportunities for land use vary strongly with management levels, and (2) a conceptual model of land suitability evaluation could offer a clear guide to geographic information system design for sustainable land use.

We must recognize that the ecologic conscience is at a turning point in history. Humanity is in a transition period, where principles should strive for the reconciliation of lifestyles (human status/behaviour) and the planet's means (nature tolerance). In this context, stewardship of both natural and human resources requires a chain of rational actions at various levels of public decision making. Top-down, this involves public-sensitive government policies based on scientific information on environmental and social-economic integration. From the bottom up, management decisions that influence the production system would need to be taken into account.

The crisis imposed by this development must be everyone's concern. For example, the issue of water availability for urban and agricultural consumption, which was a serious concern for only some countries in Africa, Asia and Latin America during the '70s, has become a worldwide problem. For this reason, integrated knowledge on the potentialities of the natural and socio-economic context is required for decision making for sustainable development at country, regional or local level.

Strong limitations hinder the integration and interpretation of such data to support decision making. First, there is the conflict of the scales of geometric representations and domain models, where the degree of detail does not tally with the degree of generalization required for planning activities. In this sense, a vertical flow of information must be established through levels of decision making, requiring models at distinct levels of data aggregation. Furthermore, links between levels must be identified for communication among them, where groups of detailed data can be aggregated/generalized at a higher level of abstraction. Second, we can observe an increasing demand for geographic information systems that serve as dynamic tools for questioning, understanding and integrating at different levels of policy making.

In Brazil, the overall scenario is no different and reflects the limitations described above. For example, São Paulo state has a high level of social-cultural and technologic development. It also has a high rate of soil loss per year [1]. At the other extreme, there is a tremendous lack of knowledge in the Amazon region about thousands of its unique micro-ecosystems, thus leading to the improper use of such human strategic resources [16].

A growing movement has emerged to question the role of agricultural legislation in promoting practices that contribute to environmental and social problems. In fact, proper policy guidelines for agricultural land use require information on both natural and social-economic potentialities. Models for agricultural land suitability and availability offer valuable information, which may become even more meaningful if modelled in the context of an information system. However, the information technology offered is usually generic and cannot support all requirements of spatial applications. For this reason, the modelling level of spatial objects is an essential bridge from the modelling of thematic abstractions (spatial objects) to the modelling of software abstractions (processes and interfaces).

The objectives of the study were to meet user needs for decision making at federal, state and regional levels, *ie*:

(1) to determine the land potential for agriculture in Brazil by physiographic region

(2) to establish a stratification of land potential according to land management levels

(3) to develop a system analysis that offers both management of attributes and geometric components in an interdisciplinary context at various levels of aggregation.

MATERIAL AND METHODS

The basic material for thematic considerations included results generated by the model of land suitability and availability in Brazil, which was the basis for the interpretation of soil surveys carried out by SUPLAN (Secretaria Nacional de Planejamento Agrícola), within the Ministry of Agriculture, for each federal state of the country [10]. Complementary criteria on evaluating land were retrieved

[1] Centro Nacional de Pesquisa de Solos (EMBRAPA-CNPS), Rua Jardim Botânico, 1 024 Jardim Botânico, 22 460-000 Rio de Janeiro RJ, Brazil

from up-to-date literature [12, 13, 5, 1]. The available GIS environments for spatial data processing were ILWIS 1.4 and Arc/Info 7.0 for DOS/Windows platforms, and SPRING for Unix platforms. The CASE tool (computer-aided software engineering) adopted for the modelling activities was the Rational Rose/C++ 4.0 [15].

The methodology was based on three different modelling theories.

(1) The abstraction of natural phenomena for land suitability and availability assessment in Brazil [12] was derived from basic data on physiographic region and management. Additional considerations were based on the method for evaluating land for improved farming systems [11] as follows:

- *Agricultural land management levels:* Three levels of land management were distinguished based on agricultural practices available to the majority of farmers, as well as technologic and social-economic aspects. They carry the following notations: A (low input—low technology adoption); B (intermediate—intermediate technology adoption); and C (high input—high technology adoption). The notations appear in different forms (upper- or lowercase letters) according to the land suitability class.
- *Agricultural land suitability groups:* Besides identifying crops as the indicated land use, groups 1, 2 and 3 represent the best land suitability according to the land management levels as A, B and C. Groups 4, 5 and 6 identify the other land utilization types as “improved pasture”, “forestry” and “rangeland wildlife”, regardless of the land suitability class. The numeric notation represents different possibilities of land use, with increasing limitations to land use from 1 to 6 and, consequently, decreasing possibilities and intensity of cultivation.
- *Land suitability classes:* These express the land suitability for a specific type of land use. They translate the degree of intensity to which land is affected by limitations. As defined in the FAO framework [4], the classes are as follows: good (no significant limitations for sustainable production); fair (moderate limitations for sustainable production); marginal (strong limitations for sustainable production); and not suitable (adverse conditions for sustainable production). The notations of possible land uses are: crops (A, B or C level); improved pasture (P); forestry (S); and rangeland (N). The notations of land suitability classes appear as letters in uppercase, lowercase, or lowercase in parentheses, according to the land suitability classes (see Table 1).

(2) The next inner level of abstraction concerns the identification and aggregation of terrain features within a given classification hierarchy in the context of the previous thematic model. The necessity to model at different levels of abstraction to translate spatial abstractions into computational geo-databases is illustrated by Molenaar [7] as in Figure 1. Each level is defined by a set of system goals, activities, data, processes and information requirements. At this point, the modelling activity resembles a disciplinary hierarchy [8]. In spatial data management, terrain features contain both thematic and geometric information. Therefore, a formal geo-information theory must be adopted to represent abstractions of terrain objects in terms of syntax, semantics and uncertainty [7]. The results are diagrams representing the semantic framework based on relationships of domain features, besides the geo-object representations and topologic relationships.

Still, different semantic levels of topology should be considered to handle the structural complexity of terrain systems. The relationships are established at three distinct levels: between geometric elements, between terrain feature objects, and between geometric elements and terrain feature objects. This requires a set of thematic and geometric keys to build up a syntax for managing geographic information complexity. The formal data structure (FDS; [7]) is based on concepts of the set theory for the mathematical normalization of lower-level syntax relationships among graphical primitives. It formalizes a topologic structure necessary to generate the field units in the semantic framework.

The remaining question of this modelling phase is addressed on the basis of the hierarchy theory outlined by O’Neill [9], which addresses scale and model integration problems of environmental systems. It presents criteria for identifying fundamental hierarchy, fundamental level, interactive state variables, principles, effects and predictions between lower and upper levels. Further references on the potential application of the theory have been given by MacMahon *et al* [6] and Webster [17].

(3) The innermost level in Figure 1 represents software components to meet user needs, in terms of simulation models of sustainable land management. Object-oriented data models support the description of both the structural and behavioural properties of a database. Structural properties relate to the static organizational nature of environmental databases. Behavioural properties are dynamic and relate to the nature of probable changes in the information and the database [18]. In this approach, the scientist must declare the nature of the real world entities first: characteristics and behavioural structure of the spatial representation [3, 14]. The architectural model proposed by the UML (Unified Modelling Language) methodology [2] examines logical, process,

TABLE 1 Notations of land suitability classes

	LAND UTILIZATION TYPES					
SUITABILITY CLASS	CROPS MANAGEMENT LEVEL			IMPROVED PASTURE MANAGEMENT LEVEL B	FORESTRY MANAGEMENT LEVEL B	RANGELAND MANAGEMENT LEVEL A
GOOD	A	B	C	P	S	N
FAIR	a	b	c	p	s	n
MARGINAL	(a)	(b)	(c)	(p)	(s)	(n)
NOT SUITABLE	_	_	_	_	_	_

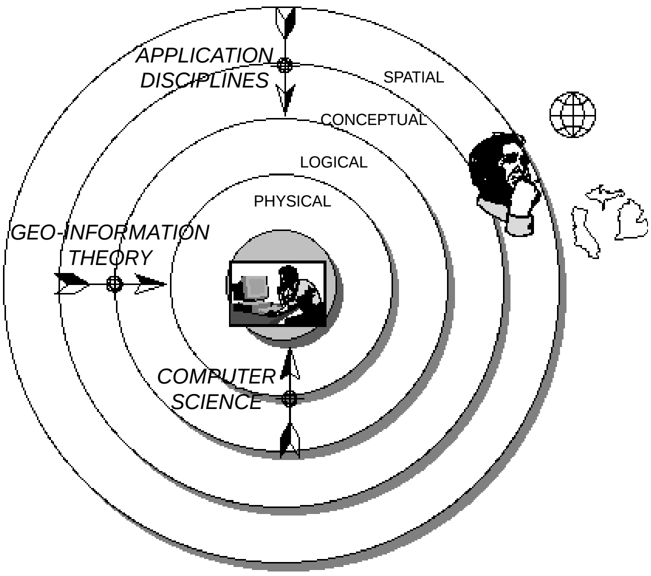

FIGURE 1 Levels for data modelling and related disciplines (after [7])

physical and development views and is built of two nested phases, dealing with macro and micro processes.

RESULTS

Results were synthesized at physiographic region level for presentation purposes. Furthermore, the basic evaluation considered specific agricultural suitability for long-cycle crops, short-cycle crops, mixed crops, two vegetative cycles per year and special crops, as well as natural parks and ecologic reserves at the state level. For this paper, however, they have been generalized as annual, semi-perennial and perennial crops.

LAND POTENTIALITIES AT NATIONAL AND REGIONAL LEVELS

From results at the national level, we could observe a great predominance of land suitable for crops: 5,498,093 km², corresponding to 65 percent of the Brazilian territory. The rest of the land suitability distribution is as follows: 12 percent for improved pasture land, 11 percent for forestry and rangeland, alongside 12 percent of land unsuitable for agricultural practices (see Table 2).

Analysis of land potentials indicates that crop production has great possibilities of diversification. There are 4,153,554 km², representing 75 percent of the total arable area, suitable for crops of short and long vegetative cycles. The areal extent that can support more intensive land utilization, ie, suitable for two crops per year or only annual crops, is 621,746 km² and 812,296 km² (11 and 15 percent of the total crop area), respectively. Long-cycle crops can still be grown in areas indicated for improved pasture, which cover 128,051 km², representing 2 percent of the total Brazilian crop land. They are lands suited for improved pasture, but still offer conditions for a more intensive use. The extent of suitable lands for special and long-cycle crops is 402,203 km², representing 7 percent of the Brazilian territory.

From the total area for ecologic parks and reserves

TABLE 2 Potential for land suitability in Brazil by physiographic regions (Figure 2)

Land utilization type	*Region*	*Area (km²)*	*Specific land suitability for crops (km²)*					*Reserve areas (km²)*
			Annual and perennial	*Annual*	*Perennial*	*Two crops per year*	*Special crops*	
Crops	N	2,792,644	1,937,365	348,476		-	-	506,803
	NE	793,159	445,268	334,038		84,663	309,118	13,853
	SE	565,741	529,805	35,105		124,454	-	831
	MW	976,763	964,532	5,819		142,207	-	6,412
	S	369,786	276,584	88,858		270,422	93,085	4,344
	Total	**5,498,093**	**4,153,554**	**812,296**		**621,746**	**402,203**	**532,243**
Improved pasture	N	288,139			5,553		-	49,091
	NE	112,191			3,334		5,055	15,832
	SE	140,425			71,095		8,555	446
	MW	361,518			25,498		-	90
	S	62,061			22,571		9,254	890
	Total	**964,334**			**128,051**		**22,864**	**66,349**
Forestry	N	13,770					-	2,125
	NE	462,967					103,704	3,539
	SE	136,470					-	270
	MW	284,215					-	1,574
	S	43,874					2,913	297
	Total	**941,296**					**106,617**	**7,805**
Not suitable	N	457,770					-	95,227
	NE	168,427					26,993	2,444
	SE	80,174					4,933	1,831
	MW	257,443					-	1,154
	S	32,295					-	785
	Total	**996,109**					**31,926**	**101,441**

(707,838 km²), 532,243 km² (75 percent) are located on lands suitable for crop production. The improved pasture is a utilization type with a potential to occupy 964,334 km², representing 11 percent of the national area. As noted above, part of these lands can accommodate long-cycle and special crops, *ie*, 13 and 2 percent, respectively. Land suitable for forestry amounts to 941,296 km², representing 11 percent of the national area. Lands with no agricultural suitability, 996,109 km², are used for flora and fauna preservation, and they represent 12 percent of the national area. From this segment, natural parks and reserves occupy 10 percent.

LAND POTENTIALITIES CONSIDERING DIFFERENT LAND MANAGEMENT LEVELS

Table 3 presents different land use types by region, according to the land suitability classes good, fair and marginal, and under land management levels A, B and C. Among the considered land use types, land suitability for crops represents a surface area of 5,498,093 km², corresponding to 65 percent of the Brazilian territory. Adopting improved land management may change this total area of crop land significantly. At management level A (low technology), it represents 3,874,707 km² of crop lands. A slight improvement in technology may raise the land management level to B (median technology), bringing the potential area to 4,982,766 km². This increase of 1.1 million km², corresponding to twice the extent of the southern region of Brazil (Figure 2), represents extraordinary agricultural prospects for more productive and profitable land use. If we consider the high technologic land management level C, a further significant increment in area results in comparison with management level A; 4,484,723 km² in total.

An analysis of crop production areas for all regions (Table 3) shows that land management level is the preponderant factor that defines crop land suitability. At land management level A, there is a clear dominance of the marginal land suitability class in all regions (Figure 3). This means that the lack of technology imposes a enormous constraint. At land management level B, there is an equilibrium between land suitability classes fair and marginal for most of the regions (Figure 4). On the other hand, at land management level C there is a strong predominance of the land suitability class fair (Figure 5). Only under land management levels B and C is it possible to observe a meaningful area delineation, notably in the Southeast, Middle West and South, which are classified as "good" crop land.

As to improved pasture land, it is possible to verify (Table 3) that the South has a high potential for this use; 56 percent (34,125 km²) of the region is of "good" suitability (Figure 6).

As for lands exclusively for forestry, 48 percent

TABLE 3 Land suitability in Brazil according management level and land utilization type

Land utilization type	*Region*	*Land suitability according to management level (km²)* Level A Good	Level A Fair	Level A Marginal	Level B Good	Level B Fair	Level B Marginal	Level C Good	Level C Fair	Level C Marginal
Crops	N	25,850	204,982	2,046,873	106,878	1,751,585	427,377	30,032	1,731,001	326,120
	NE	13,394	145,079	435,307	15,555	421,060	321,150	7,482	436,452	267,025
	SE	22,715	118,648	147,506	102,929	130,785	330,767	78,230	266,287	45,966
	MW	2,508	68,048	358,065	10,708	385,902	579,222	107,426	636,919	231,460
	S	46,191	96,824	142,717	64,975	171,474	162,399	38,388	233,857	48,078
	Total	**110,658**	**633,581**	**3,130,468**	**301,045**	**2,860,806**	**1,820,915**	**261,558**	**3,304,516**	**918,649**
* Improved pasture	N				-	243,133	4,935			
	NE				4,908	91,636	27,967			
	SE				2,957	40,215	96,807			
	MW				-	339,309	22,119			
	S				34,125	16,836	10,210			
	Total				**41,990**	**722.109**	**162,038**			
** Forestry	N				-	-	3,816			
	NE				1,939	33,908	71,854			
	SE				-	58,619	9,415			
	MW				-	139,418	71,006			
	S				3,127	7,322	11,238			
	Total				**5,066**	**239,267**	**167,329**			
*** Rangeland	N	-	-	9,469						
	NE	287	141,564	290,781						
	SE	-	945	77,084						
	MW	-	-	209,181						
	S	19,789	10,359	3,102						
	Total	**20,076**	**152,868**	**589,617**						

Source: [10]

* Land exclusive for improved pasture; not suitable for crops
** Land exclusive for forestry; not suitable for both crops and improved pasture
*** Land exclusive for existing rangeland

(10,449 km²) of the lands in the South are suitability class good to fair (14 and 34 percent, respectively). The remaining area (11,238 km² or 52 percent of the region) is marginal. The Northeast has 33,908 km² (31 percent of the region) classified as fair and 1,939 km² (2 percent of the region) classified as good, but marginal suitability applies to 67 percent of the region (71,854 km²) (Figure 7 and Table 3).

An analysis of rangeland shows (Table 3) once more that the South has good suitability for this use—60 percent (19,789 km²) of the entire region. In addition, the Northeast has the following results: 33 percent of the region (141,564 km²) is fair; and 67 percent of the region (290,781 km²) is marginally suitable. The remaining regions (the North, Middle West and Southeast) have almost exclusively marginal rangeland suitability (Figure 8).

FIGURE 2 Physiographic regions (North, Northeast, Southeast, Middle West and South) of Brazil

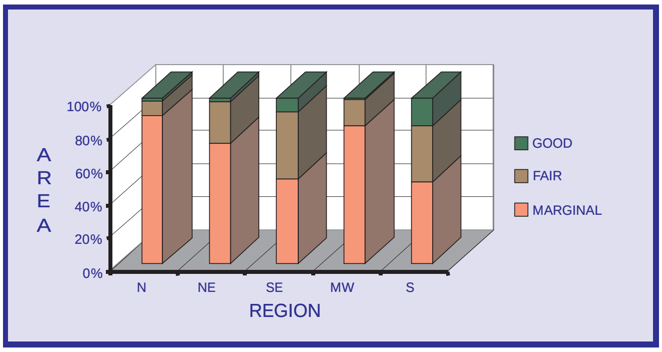

FIGURE 3 Land suitability classes for crops under management level A

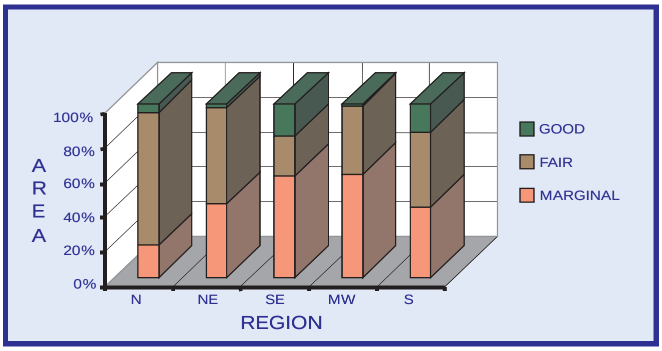

FIGURE 4 Land suitability classes for crops under management level B

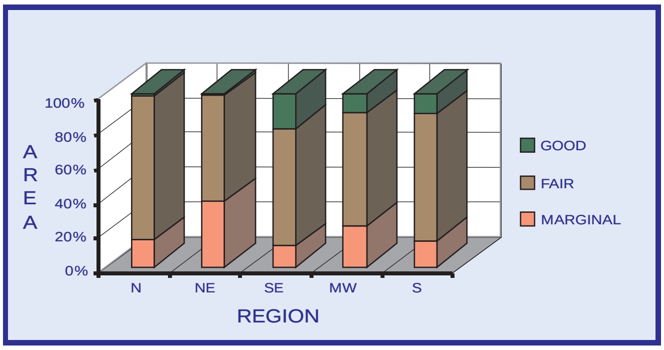

FIGURE 5 Land suitability classes for crops under management level C

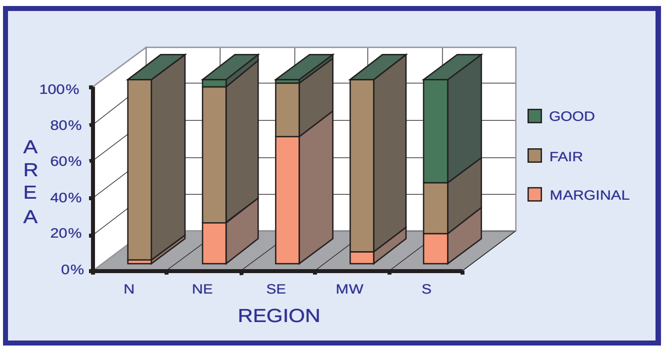

FIGURE 6 Land suitability classes for improved pasture under management level B (obs: exclusive for improved pasture; not suitable for crops

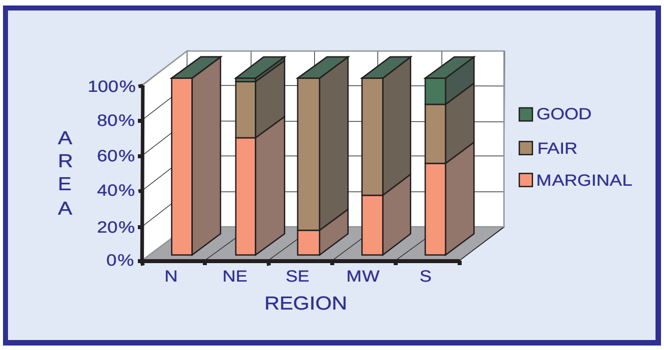

FIGURE 7 Land suitability classes for forestry under management level B (obs: exclusive for forestry; not suitable for crops or improved pasture)

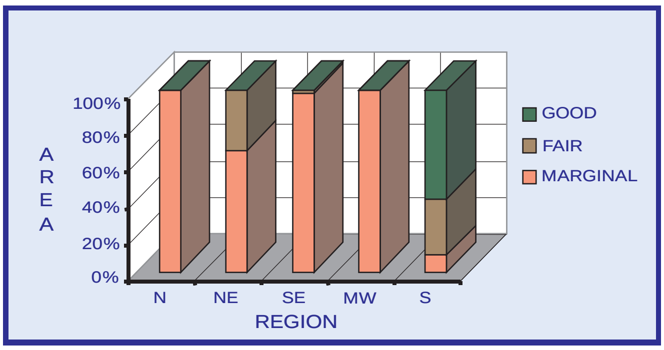

FIGURE 8 Land suitability classes for rangeland under management level A

CONCEPTUAL MODEL

The preliminary results of geographic information system analysis include a set of diagrams that present, at a conceptual level, identified interactions between system interfaces and thematic models. For this presentation, the main conceptual class diagrams were selected after they had passed the consistence check (Figure 9). It is clear that this does not represent any revolutionary paradigm in terms of analysis, but indeed a promising engineering perspective for addressing complexity in software development.

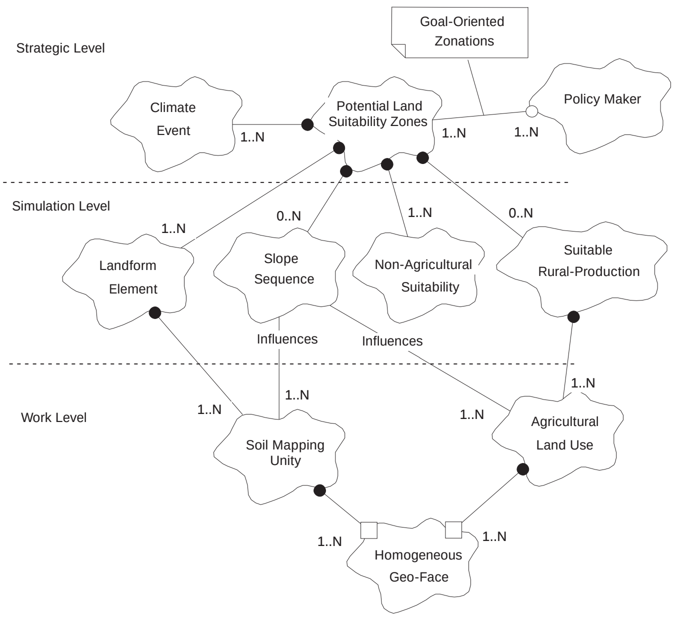

FIGURE 9 Conceptual diagram representing critical interactions for simulating scenario on model integration

The use of a software environment for modelling offers an interface between analysis and design through icons and menus, changing options according to the selected diagram or object class. A model validation option of the adopted CASE checked the complete model, detecting no inconsistencies in terms of definitions of class categories, object classes, relationships and scenario interactions (Figure 10). Another advantage has been to have an automatic report generator of the entire data dictionary. An option called “reverse engineering” also offers the possibility of automatic generation of object-oriented programming code, and its reverse transformation from code to model after possible adjustments. The result of using the CASE tool for object-oriented analysis is considered very satisfactory. However, a complete set of definitions is required in order to automatically generate the programming code demanding knowledge about the language itself.

FINAL REMARKS

At the level of detail addressed in this paper, and also, considering the synoptic view of the broader scope of this land evaluation, the following remarks are still relevant:

(1) Brazil has a tremendous potential for agriculture. Its land potential can be summarized as: 5.5 million km^2 (550 million ha) suitable for crops; 964,334 km^2 suitable for improved pasture; 941,296 km^2 suitable for forestry and rangeland (good, fair and marginal).

(2) Land potentialities with the land management level considered are relevant to planners.

(3) Although there is an effort and interest to establish, monitor and increase natural conservation units, parks and reserves, Brazil is still committed to increase the preservation and maintenance of its biodiversity and would benefit greatly from stepping up its land evaluation efforts.

(4) The use of geo-information modelling is essential for development. The method discussed has demonstrated that spatial and analytical models supplement each other in applications involving natural terrain phenomena.

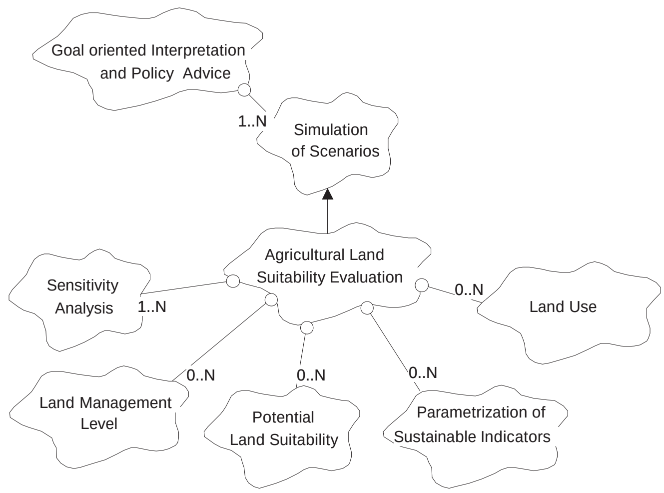

FIGURE 10 Conceptual diagram representing critical interactions for simulating scenario on model integration

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RESUME

Certains ordres du jour de recherche demandent une connaissance des potentialités des ressources naturelles ainsi que le contexte socio-économique afin de fournir une information significative pour un développement durable. Mais il y a de fortes limites pour intégrer et interpréter de telles données. Les objectifs de cette étude étaient de (1) de déterminer le potentiel naturel de la terre pour l'agriculture au Brésil, par région physiographique; (2) d'établir une stratification du potentiel de terre suivant les niveaux de gestion de terre; et (3) de développer un système d'analyse qui offre à la fois la gestion des attributs ainsi que la simulation des scénarios. La méthodologie se basait sur différents niveaux d'abstraction: modélisation quantitative des phénomènes naturels pour l'aptitude et la disponibilité des terres, au Brésil; modélisation conceptuelle des détails du terrain; et modélisation d'ingéniérie logicielle pour répondre à la demande des utilisateurs. Les résultats partiaux comprennent une stratification des potentialités d'utilisation des terres suivant des niveaux technologiques de gestion. La répartition de zones, par aptitude de production de récolte indique que la gestion avec adoption de technologie joue un rôle important pour augmenter la production agricole. Les conclusions sont: (1) le Brésil a un énorme potentiel en agriculture, dans lequel les occasions d'utilisation des terres varient fortement avec les niveaux de gestion; (2) un modèle conceptuel d'évaluation d'aptitude des terres pourrait offrir un bon guide à un projet de système d'information géographique pour une utilisation durable des terres.

RESUMEN

Ciertos programas de investigación requieren un conocimiento de las potencialidades de los recursos naturales y del contexto socio-económico para suministrar información significativa para el desarrollo sostenible. Sin embargo, hay grandes limitaciones para integrar e interpretar tales datos. Los objetivos de este estudio eran de (1) determinar el potencial natural de las tierras para agricultura en Brasil por región fisiográfica; (2) establecer una estratificación del potencial de las tierras de acuerdo a los niveles de manejo de las mismas; y (3) desarrollar un análisis de sistema que permita tanto la manipulación de atributos como la simulación de escenarios. La metodología se basó en diferentes niveles de abstracción: modelaje cuantitativo de fenómenos naturales para la aptitud y la disponibilidad de tierras en Brasil, modelaje conceptual de objetos de terreno, y modelaje de la ingenería de programas para satisfacer las demandas de los usuarios. Los resultados parciales incluyen una estratificación de las potencialidades de uso de las tierras de acuerdo a niveles tecnológicos de manejo. La distribución geográfica por aptitud de producción de cultivos sugiere que el manejo con adopción de tecnología juega un papel importante en incrementar la producción agrícola. Las conclusiones son las siguientes: (1) Brasil tiene un potencial enorme para la agricultura, en el cual las oportunidades para el uso de las tierras varí-