

Postdoctoral research report No. _____

**2-D Stochastic Simulation Of Spatial Distribution Of
Soil Layers And Types Using
The Coupled Markov-Chain Method**

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Abstract

The spatial variation of soil layers and types is a typical feature of soils. The coupled Markov-chain method was used to simulate the spatial distribution of soil layers and types. The simulation of soil textural transections was conducted using data from a 15km² alluvial soil region in North China Plain. The results show that this method can basically describe the spatial change of 4 types of textural layers and the simulated images are similar to the hand-drawn ones each based on a row of observed profiles. An obvious problem is that soil textural layers in the simulated transections are inclined with being related to the simulation proceeding direction. Some hypothetical ideal data was used to reproduce the variability of thickness of the horizons in a genetic soil profile. Results indicate that the transections of genetic soils can also be roughly simulated with saw-toothed borders between neighboring horizons. Soil type maps are also simulated using this method. It appears that images of soil maps with multiple types can be generated to show the spatial variability of soil types if the distribution of all soil types is statistically homogeneous. But if parcels of some types occur sparsely in the original they can not be generated and displayed suitably, because the parameters calculated from the original map can not reflect the probabilistic law ruling the spatial distribution of soil types. So the estimation of parameters is a key step in this method. It seems that this method is full of potentials in the future because of its simplicity and clarity though there are some problems need to be further studied.

1. Introduction

The spatial variation of soil layers and types is a typical feature of soils, particularly the spatial variation of soil textural layers in alluvial soils. It is shown by the variable layers in soil transections and by the parcels of soil types on soil surface. The spatial variation of soil textures influences the water flow and solute transport and, ultimately, the growth of crop roots on soils or the movement of nutrients (e.g. nitrogen), pesticides and contaminants through the soil. Given the important effect of heterogeneity on flow and transport processes for the specific simulations, the 'exact' spatial distribution of 'critical' soil properties should be known. In most cases, however, the distribution or variability is subject to uncertainty. Therefore, a crucial step in the simulation of water flow and solute transport through heterogeneous porous media (i.e. soil) is to define a probabilistic model to describe the spatial variability of a given variable such as soil texture or soil type. In this study, two discrete variables (soil textural class and soil type) are considered. In this study, the starting hypotheses are that the two-dimensional spatial distribution of these variables can be described with a Markov-chain model, and that its statistical parameters can be used to generate stochastically identical images of the spatial distribution of the discrete variables.

The one-dimensional Markov-chain (MC) method has been widely used in geology to simulate the transitions of strata from 1960s (Harbaugh and Merriam, 1968; Harbaugh and Bonham-Carter, 1980;

Krumbein, 1968). Li, et al. (1997, 1999) has used this method to simulate the spatial distribution of textural layers of alluvial soils at a regional scale. Recently, Elfeki (1996) presented a coupled Markov-chain method to simulate two-dimensionally geological formations. He used some hypothetical ideal data to test this method and thought it was feasible to characterize geological heterogeneity.

The coupled Markov-chain method is used in this study to simulate the spatial distribution of soil layers and types. The objectives of the study are (i) to estimate the statistical parameters of a 2D Markov chain model from observed 2D spatial distribution of 2 discrete variables (soil textural class and soil type), (ii) to develop an algorithm to stochastically simulate 2D-images of the soil textural or soil type distribution using a Markov chain Monte Carlo, and (iii) to evaluate the proposed method by qualitatively and quantitatively compare images with observed maps. The results show that there are still some problems to need to be further studied in this method before it can be applicable effectively.

2. Theory

2.1. The two-dimensional independent first-order stationary MC

A Markov-chain is a probabilistic model that exhibits a special type of dependence: the future state only depends on the present state and not on the past states. In this manner, the state of the system at any time (in case of time series) or space (in case of space series) is stochastically determined by its state at the preceding time or space step. Suppose that $Z_0, Z_1, Z_2, \dots, Z_m$ is a sequence of random variables defined on the state space $[S_1, S_2, \dots, S_n]$. The sequence is a Markov-chain if,

$$p[Z_k = S_j | Z_{k-1} = S_i, Z_{k-2} = S_n, \dots, Z_1 = S_q, Z_0 = S_p] = p[Z_k = S_j | Z_{k-1} = S_i] = p_{ij} \quad (1)$$

where the symbol 'I' is a symbol for the conditional probability, which means the probability of occurrence of a certain state given that other states have already occurred and p_{ij} is the transition probability from state S_i to State S_j . In this study, only the first-order stationary Markov-chain is considered.

An 1-D Markov-chain is described by a single transition probability matrix (TPM) P :

$$P = \begin{bmatrix} p_{11} & p_{12} & \dots & p_{1n} \\ p_{21} & p_{22} & \dots & p_{2n} \\ \dots & \dots & \dots & \dots \\ p_{n1} & p_{n2} & \dots & p_{nn} \end{bmatrix} \quad (2)$$

where p_{ij} signifies the probability of transition from state S_i to state S_j , and n is the number of states in the system. This matrix P has follow characteristics: (1) its elements are not negative ($p_{ij} \geq 0$); (2) the elements of

each row sum up to one ($\sum_{j=1}^n p_{ij}, i=1, 2, \dots, n$).

The marginal probability distribution can be obtained by multiplying the single-step transition probability matrix by itself many times until all rows in matrix become identical. It may be expressed by

$$W = (w_1, w_1, \dots, w_n) \quad (3)$$

where w_i is the marginal probability of state $i, i=1, 2, \dots, n$, which is no longer dependent of the initial state, and (w_1, w_1, \dots, w_n) is any one row of the limit matrix LP :

$$LP = \lim_{m \rightarrow \infty} P^m \quad (4)$$

where m is a power index.

In this research a coupled chain is used to describe the behaviour of a two-dimensional Markov-chain process. Each chain is a classical first-order Markov-chain. They are perpendicular each other at x - and y -directions and thought to be independent of each other. We use the joint conditional probability of state pairs in two chains to express the state change of the system at two-dimensional space. Consider two one-dimensional first-order Markov-chains $X_m, Y_m, m=1, 2, \dots$, both defined on the state space $[S_1, S_2, \dots, S_n]$, we can have the joint transition probability defined as

$$p[X_{m+1}=S_i, Y_{m+1}=S_k | X_m=S_i, Y_m=S_j]=p(ij, lk) \quad (5)$$

We assume that the two Markov chains are independent of each other, then the joint transition probability can be given by

$$p(ij, lk) = p_{il} \bullet p_{jk} \quad (6)$$

The marginal distribution of the coupled chain is given by

$$w(lk) = w_l \bullet w_k \quad (7)$$

2.2. Inference of statistical parameters

A Markov chain is completely described when the state space, transition probabilities and initial probabilities are given.

The state space can be determined according to the actual need. For example, we can divided soil texture into several types such as sand, sand loam, loam and clay, etc. if they are important and occur widely in a research region. The transition probabilities can be determined by superimposing a lattice on a soil transection. The transition frequencies between the states at x - or y -direction are calculated by counting the times a given state say S_i followed by itself or the other states say S_j at the direction on the lattice and then dividing by the total number of transitions,

$$p_{ij} = T_{ij} / \sum_{j=1}^n T_{ij} \quad (8)$$

where, T_{ij} is the number of observed transitions from state i to state j at the (x - or y -) direction on the lattice. The cumulative transition probability is computed by the formula,

$$P_{ik} = \sum_{j=1}^k p_{ij}, \quad k=1, \dots, n \quad (9)$$

This cumulative probability distribution is used to realize the chain.

The marginal probability is defined as the probability of occurrence of a given state in the system regardless the states of the neighboring cells. One can get the marginal probability, w_i , by summing the columns of the transition frequency matrix and dividing these column totals by the grand total of the transitions as

$$w_i = \frac{\sum_{i=1}^n T_{ij}}{\sum_{i=1}^n \sum_{j=1}^n T_{ij}} \quad (10)$$

In case of two transition probability matrices in the x - and y -directions, w_i is obtained as:

$$w_i = \frac{\sum_{i=1}^n T_{ij}^x + \sum_{i=1}^n T_{ij}^y}{\sum_{i=1}^n \sum_{j=1}^n T_{ij}^x + \sum_{i=1}^n \sum_{j=1}^n T_{ij}^y} \quad (11)$$

where T_{ij}^x is the x -directional transition frequency between state S_i and S_j , and T_{ij}^y is the y -directional transition frequency between state S_i and S_j .

A complete code was written to calculate the TPM (See code in Appendix A).

3. Markov-chain Monte Carlo Method

3.1. Simulation principle

Consider a two dimensional domain of cells as shown in Fig. 1. Each cell has a row number l and a column number k . Consider also a given number of soil materials say n , such as sand, loam, clay, etc. These soil materials are coded, for example, 1 for sand, 2 for loam and 3 for clay, etc. If two first-order Markov chains are used to describe the spatial change process of states in this two-dimensional domain at x - and y -directions, the joint probability of the lattice process can be expressed mathematically as:

$$\begin{aligned} p(Z_{1,1}=S_1, Z_{2,1}=S_2, \dots, Z_{k,l}=S_b, Z_{k-1,l}=S_j, Z_{k,l-1}=S_q, \dots, Z_{m_x,m_y}=S_p) = \\ p(Z_{m_x,m_y}=S_p | Z_{m_x-1,m_y}=S_g, Z_{m_x,m_y-1}=S_h) \bullet \dots \bullet \\ p(Z_{k,l}=S_i | Z_{k-1,l}=S_b, Z_{k,l-1}=S_f) \bullet \dots \bullet \\ p(Z_{2,2}=S_4 | Z_{1,2}=S_3, Z_{2,1}=S_2) \bullet \\ p(Z_{n,1}=S_c | Z_{n-1,1}=S_d) \bullet \dots \bullet p(Z_{2,1}=S_2 | Z_{1,1}=S_1) \bullet \\ p(Z_{1,m}=S_r | Z_{1,m-1}=S_i) \bullet \dots \bullet p(Z_{1,2}=S_3 | Z_{1,1}=S_1) \bullet \\ p(Z_{1,1}=S_1) \end{aligned} \quad (12)$$

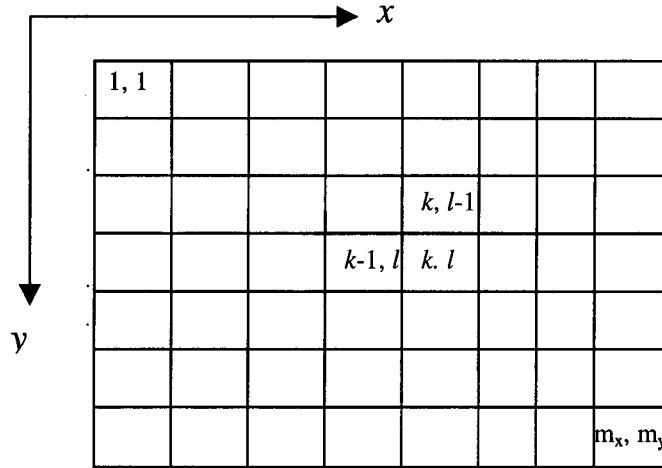


Fig. 1. A two-dimensional domain of cells.

For the conditioned boundary cells, the state change is described by classical first-order Markov chain. A conditional probability in upper x-directional boundary is

$$p(z_{k,1}=S_j | z_{k-1,1}=S_i) = p_{ij}, \quad k=1, 2, \dots, m_x. \quad (13)$$

Similarly, a conditional probability in left y-directional boundary is

$$p(z_{1,l}=S_u | z_{1,l-1}=S_v) = p_{vu}, \quad l=1, 2, \dots, m_y. \quad (14)$$

For the rest cells on the lattice, the conditional probabilities are calculated by coupling both x- and y-directional chains. A joint conditional probability at anyone cell on the lattice is given by

$$p(z_{k,l}=S_j | z_{k-1,l}=S_i, z_{k,l-1}=S_h) = p(z_{k,l}=S_j | z_{k-1,l}=S_i) \cdot p(z_{k,l}=S_j | z_{k,l-1}=S_h) = p_{ij} \cdot p_{hj} \quad (15)$$

In Eq.15, $\sum_{j=1}^n p_{ij} \cdot p_{hj}$ is not equal to one, since i and h are fixed. Therefore, during Monte-Carlo sampling, the joint transition probabilities should be normalized:

$$p = (p_{ij} \cdot p_{hj}) / \sum_{j=1}^n (p_{ij} \cdot p_{hj}) \quad (16)$$

3.2. Implementation procedures

Monte-Carlo method is used to conduct sampling in the stochastic simulation. A procedure for unconditional simulation involves the following set of instructions using Eq.(12) in a sequential order:

Step 1: The two-dimensional domain is discretized using proper sampling intervals (grid cell sizes) (See Fig.1).

Step 2: Select an initial state at cell (1, 1), the upper-left corner, using the Monte-Carlo sampling method randomly from the marginal distribution of the states, $W = (w_1, w_1, \dots, w_n)$ if it is known, or randomly

from the given states in the system, if the distribution is not known. The choice between the different states can be realized by solving the following equation:

$$\sum_{l=1}^{k-1} w_l < r_1 \leq \sum_{l=1}^k w_l, \quad k=2, \dots, n \quad (17)$$

Step 3: Start from cell (1, 1), generate upper boundary cells (k, 1), k=1, 2, ..., m_x from the x-directional TPM.

Step 4: Similarly, from cell (1, 1), generate the left boundary cells (1, l), l=1, 2, ..., m_y from the y-directional TPM.

Step 5: generate the rest of the cells with numbers (k, l), k=2, ..., m_x and l=2, ..., m_y in the domain row by row using the joint conditional probability distribution of the x-directional Markov-chain and the y-directional one.

3.3. Conditional simulation on field data

If two neighboring boundaries are known, the conditional simulation on field data can be conducted and is straightforward. Instead of generating the initial cell state and upper and left boundary cell states from the derived marginal and transition probabilities, one can assign at each cell on the boundaries the corresponding states from the measured data. In this research, only the conditional simulation is conducted.

Some Fortran computer programs for simulation of spatial distributions of soil textural types are given in Appendix B.

4. Results and discussions

4.1. Simulation of alluvial soil transections

The research region is a rectangular area of 15km², located near the Quzhou Experiment Station of China Agricultural University, in North China Plain. There are 142 observed soil profile pits arranged on a grid with 9 rows in east-west direction. The soil texture is divided into 4 classes, coded with 1 for sand, 2 for sand loam, 3 for loam and 4 for clay, respectively. Based on these observed profiles, we can draw 9 soil textural transections with a depth of 2m and a length of about 5500m. Conditioned on the upper and left boundaries, a series of conditional stochastic simulations are conducted for these soil transections using the above two-dimensional Markov Chain method. Table 1 shows the statistics from Transection 9 and its 8 simulated realizations. The input statistics and the calculated statistics are very similar. But some differences occur between the image of the hand-drawn transection and those of its realizations (Fig.2). The simulated transections show some inclined and more connective bands of soil textural layers compared with the hand-drawn one, particularly because of unequal cell sizes at x- and y-directions.

Table 1. Statistics of Transection 9 and its 8 realizations (using TPMs and boundaries only from Transection 9)

		Cell size in x-direction = 10m Cell size in y-direction = 5cm								
		TPM at x-direction				TPM at y-direction				
	State	1	2	3	4	State	1	2	3	4
Input	1	0.9858	0.0017	0.0066	0.0059	1	0.9394	0.0000	0.0424	0.0182
	2	0.0000	0.9893	0.0036	0.0071	2	0.0119	0.8988	0.0417	0.0476
	3	0.0079	0.0049	0.9807	0.0065	3	0.0333	0.0250	0.8167	0.1250
	4	0.0067	0.0045	0.0039	0.9849	4	0.0702	0.0175	0.0351	0.8772
Realization	1	0.9916	0.0005	0.0021	0.0058	1	0.9756	0.0000	0.0137	0.0107
	2	0.0000	0.9888	0.0023	0.0088	2	0.0044	0.8877	0.0141	0.0937

1	3	0.0110	0.0120	0.9679	0.0090	3	0.0639	0.0689	0.6104	0.2567
	4	0.0019	0.0031	0.0012	0.9938	4	0.0525	0.0101	0.0067	0.9307
Realization 2	1	0.9895	0.0022	0.0021	0.0063	1	0.9611	0.0000	0.0173	0.0216
	2	0.0000	0.9858	0.0031	0.0110	2	0.0356	0.8665	0.0216	0.0763
	3	0.0170	0.0116	0.9624	0.0090	3	0.0450	0.1059	0.5820	0.2671
	4	0.0068	0.0034	0.0012	0.9885	4	0.0694	0.0176	0.0100	0.9030
Realization 3	1	0.9924	0.0009	0.0020	0.0047	1	0.9734	0.0000	0.0108	0.0158
	2	0.0000	0.9889	0.0033	0.0078	2	0.0220	0.8896	0.0274	0.0610
	3	0.0106	0.0205	0.9629	0.0061	3	0.1061	0.0932	0.6485	0.1523
	4	0.0132	0.0075	0.0022	0.9772	4	0.1272	0.0204	0.0057	0.8466
Realization 4	1	0.9890	0.0010	0.0043	0.0057	1	0.9746	0.0000	0.0079	0.0175
	2	0.0000	0.9850	0.0028	0.0122	2	0.0149	0.8695	0.0253	0.0903
	3	0.0123	0.0151	0.9509	0.0217	3	0.1300	0.0860	0.5507	0.2333
	4	0.0057	0.0052	0.0010	0.9882	4	0.0478	0.0147	0.0144	0.9231
Realization 5	1	0.9942	0.0014	0.0021	0.0023	1	0.9775	0.0000	0.0183	0.0042
	2	0.0000	0.9883	0.0055	0.0062	2	0.0174	0.8818	0.0278	0.0731
	3	0.0217	0.0140	0.9598	0.0045	3	0.0640	0.1462	0.6632	0.1266
	4	0.0055	0.0082	0.0018	0.9845	4	0.1205	0.0217	0.0066	0.8511
Realization 6	1	0.9891	0.0008	0.0014	0.0088	1	0.9786	0.0000	0.0002	0.0212
	2	0.0000	0.9895	0.0033	0.0072	2	0.0090	0.9064	0.0354	0.0492
	3	0.0006	0.0165	0.9791	0.0039	3	0.0198	0.0467	0.7603	0.1732
	4	0.0054	0.0031	0.0014	0.9901	4	0.0533	0.0113	0.0047	0.9308
Realization 7	1	0.9874	0.0000	0.0028	0.0098	1	0.9795	0.0000	0.0025	0.0180
	2	0.0000	0.9863	0.0039	0.0098	2	0.0002	0.8673	0.0458	0.0867
	3	0.0023	0.0112	0.9724	0.0141	3	0.0241	0.0341	0.7259	0.2159
	4	0.0020	0.0021	0.0016	0.9944	4	0.0361	0.0079	0.0079	0.9481
Realization 8	1	0.9911	0.0021	0.0023	0.0045	1	0.9708	0.0000	0.0130	0.0162
	2	0.0000	0.9897	0.0027	0.0076	2	0.0152	0.9022	0.0184	0.0642
	3	0.0134	0.0108	0.9713	0.0045	3	0.0379	0.0594	0.7422	0.1606
	4	0.0078	0.0063	0.0013	0.9845	4	0.0901	0.0290	0.0059	0.8750

Different grid cell sizes are used to generate the simulation realizations, but show no obvious effect on the images of realizations (Table 2, and Fig.3).

Table 2. Some realizations of Transection 1 with different cell sizes using the TPMs and boundaries only from Transection 1

		Cell size in x-direction = 10m Cell size in y-direction = 5cm								
		TPM at x-direction				TPM at y-direction				
	State	1	2	3	4	State	1	2	3	4
Input	1	0.9827	0.0053	0.0032	0.0088	1	0.9423	0.0048	0.0096	0.0433
	2	0.0065	0.9815	0.0077	0.0043	2	0.0602	0.8722	0.0451	0.0226
	3	0.0136	0.0069	0.9762	0.0033	3	0.0336	0.0336	0.8655	0.0672

	4	0.0102	0.0018	0.0038	0.9842	4	0.0427	0.0183	0.0305	0.9085
Realization 1	1	0.9883	0.0027	0.0010	0.0080	1	0.9525	0.0040	0.0036	0.0399
	2	0.0064	0.9827	0.0052	0.0058	2	0.0789	0.8521	0.0448	0.0242
	3	0.0160	0.0198	0.9611	0.0032	3	0.0162	0.0467	0.7917	0.1454
	4	0.0051	0.0005	0.0019	0.9925	4	0.0196	0.0071	0.0034	0.9699
Realization 2	1	0.9831	0.0028	0.0008	0.0133	1	0.9376	0.0005	0.0018	0.0602
	2	0.0003	0.9918	0.0044	0.0035	2	0.0840	0.8797	0.0313	0.0050
	3	0.0167	0.0087	0.9679	0.0068	3	0.0315	0.0258	0.8131	0.1296
	4	0.0152	0.0001	0.0016	0.9831	4	0.0600	0.0028	0.0083	0.9289

Cell size in x-direction = 10m

Cell size in y-direction = 1cm

		TPM at x-direction				TPM at y-direction				
	State	1	2	3	4	State	1	2	3	4
Input	1	0.9827	0.0053	0.0032	0.0088	1	0.9888	0.0009	0.0019	0.0084
	2	0.0065	0.9815	0.0077	0.0043	2	0.0120	0.9744	0.0090	0.0045
	3	0.0136	0.0069	0.9762	0.0033	3	0.0067	0.0067	0.9733	0.0134
	4	0.0102	0.0018	0.0038	0.9842	4	0.0082	0.0035	0.0059	0.9824
Realization 3	1	0.9828	0.0040	0.0013	0.0119	1	0.9862	0.0006	0.0004	0.0128
	2	0.0065	0.9822	0.0057	0.0056	2	0.0127	0.9724	0.0122	0.0027
	3	0.0073	0.0132	0.9744	0.0051	3	0.0039	0.0072	0.9603	0.0286
	4	0.0066	0.0005	0.0013	0.9916	4	0.0046	0.0012	0.0020	0.9922
Realization 4	1	0.9852	0.0033	0.0010	0.0105	1	0.9884	0.0006	0.0004	0.0106
	2	0.0104	0.9826	0.0044	0.0027	2	0.0222	0.9676	0.0084	0.0019
	3	0.0251	0.0202	0.9495	0.0052	3	0.0112	0.0135	0.9317	0.0436
	4	0.0083	0.0002	0.0008	0.9907	4	0.0066	0.0003	0.0008	0.9923

Cell size in x-direction = 50m

Cell size in y-direction = 1cm

		TPM at x-direction				TPM at y-direction				
	State	1	2	3	4	State	1	2	3	4
Input	1	0.9125	0.0269	0.0162	0.0444	1	0.9888	0.0009	0.0019	0.0084
	2	0.0324	0.9072	0.0388	0.0216	2	0.0120	0.9744	0.0090	0.0045
	3	0.0679	0.0345	0.8810	0.0167	3	0.0067	0.0067	0.9733	0.0134
	4	0.0513	0.0093	0.0194	0.9200	4	0.0082	0.0035	0.0059	0.9824
Realization 5	1	0.9484	0.0126	0.0117	0.0273	1	0.9942	0.0002	0.0008	0.0049
	2	0.0349	0.8563	0.0927	0.0162	2	0.0274	0.9565	0.0156	0.0004
	3	0.0714	0.0469	0.8467	0.0349	3	0.0153	0.0098	0.9615	0.0135
	4	0.0925	0.0006	0.0152	0.8916	4	0.0112	0.0013	0.0122	0.9753
Realization 6	1	0.8987	0.0163	0.0002	0.0848	1	0.9857	0.0003	0.0009	0.0131
	2	0.0286	0.9259	0.0211	0.0245	2	0.0149	0.9705	0.0066	0.0080
	3	0.0911	0.0750	0.8185	0.0153	3	0.0008	0.0107	0.9525	0.0360
	4	0.0425	0.0040	0.0066	0.9469	4	0.0065	0.0020	0.0005	0.9910

Cell size in x-direction = 2m

Cell size in y-direction = 5cm

		TPM at x-direction				TPM at y-direction			
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	State	1	2	3	4	State	1	2	3	4
Input	1	0.9965	0.0011	0.0006	0.0018	1	0.9423	0.0048	0.0096	0.0433
	2	0.0013	0.9963	0.0015	0.0009	2	0.0601	0.8722	0.0451	0.0226
	3	0.0027	0.0014	0.9952	0.0007	3	0.0336	0.0336	0.8656	0.0672
	4	0.0020	0.0004	0.0008	0.9968	4	0.0427	0.0183	0.0305	0.9085
Realization 7	1	0.9966	0.0003	0.0001	0.0030	1	0.9308	0.0011	0.0018	0.0662
	2	0.0011	0.9970	0.0009	0.0010	2	0.0586	0.8636	0.0641	0.0138
	3	0.0036	0.0042	0.9918	0.0004	3	0.0513	0.0246	0.7361	0.1879
	4	0.0031	0.0001	0.0005	0.9964	4	0.0847	0.0054	0.0031	0.9068
Realization 8	1	0.9961	0.0007	0.0001	0.0032	1	0.9183	0.0023	0.0011	0.0784
	2	0.0014	0.9965	0.0012	0.0009	2	0.0587	0.8667	0.0340	0.0406
	3	0.0010	0.0024	0.9957	0.0010	3	0.0090	0.0380	0.8667	0.0863
	4	0.0024	0.0002	0.0003	0.9972	4	0.0501	0.0079	0.0185	0.9235

The above simulation is based on the TPMs from single transection. If we consider all these 9 transections as samples of the vertically two-dimensional distribution of soil textures at east-west direction in the regions, we can calculate the total TPMs from the 9 transections. The total TPMs express the total situation of soil textural distribution in vertical two-dimensions at east-west direction in the region.

Using the total TPMs and some boundary conditions from the region (e.g. boundary conditions of the 9 transections), we can generate some conditional realizations of soil transections in the region (Table 3, 4, 5 and Fig. 4, 5, 6). These realizations can give us an insight into the spatial distribution of soil textures in the region.

A typical feature is that in simulated soil transections textural layers show inclined stripes other than horizontal. The inclined direction is related to the simulating direction.

Table 3. Statistics of three realizations based on the boundaries of Transection 9 and the total TPMs

Cell size in x-direction = 10m Cell size in y-direction = 5cm										
TPM at x-direction					TPM at y-direction					
	State	1	2	3	4	State	1	2	3	4
Input (total)	1	0.9847	0.0041	0.0042	0.0070	1	0.9356	0.0018	0.01945	0.0432
	2	0.0040	0.9899	0.0030	0.0032	2	0.0231	0.9056	0.03898	0.0323
	3	0.0085	0.0070	0.9789	0.0056	3	0.0438	0.0288	0.82814	0.0992
	4	0.0076	0.0037	0.0044	0.9843	4	0.0708	0.0166	0.03757	0.8750
Realization 1	State	1	2	3	4	State	1	2	3	4
	1	0.9893	0.0071	0.0002	0.0035	1	0.9747	0.0015	0.0024	0.0214
	2	0.0023	0.9896	0.0025	0.0055	2	0.0218	0.9258	0.0105	0.0419
	3	0.0029	0.0202	0.9726	0.0043	3	0.0000	0.1361	0.7683	0.0956
4	0.0070	0.0110	0.0025	0.9794	4	0.0983	0.0705	0.0063	0.8249	
Realization 2	State	1	2	3	4	State	1	2	3	4
	1	0.9867	0.0049	0.0019	0.0064	1	0.9642	0.0030	0.0022	0.0305
	2	0.0038	0.9927	0.0018	0.0017	2	0.0139	0.9520	0.0157	0.0183
	3	0.0077	0.0222	0.9624	0.0077	3	0.0924	0.1540	0.6450	0.1086
4	0.0092	0.0052	0.0034	0.9822	4	0.1125	0.0210	0.0158	0.8507	
	State	1	2	3	4	State	1	2	3	4

Realization 3	1	0.9891	0.0035	0.0010	0.0063	1	0.9665	0.0022	0.0003	0.0310
	2	0.0044	0.9901	0.0028	0.0027	2	0.0137	0.9373	0.0144	0.0347
	3	0.0010	0.0167	0.9796	0.0026	3	0.0225	0.1137	0.8172	0.0466
	4	0.0164	0.0148	0.0008	0.9681	4	0.1866	0.0472	0.0111	0.7551

Table 4. Statistics of some Realizations using the total TPMs and different boundaries from observed transections

		Cell size in x-direction = 10m Cell size in y-direction = 5cm								
		TPM at x-direction				TPM at y-direction				
	State	1	2	3	4	State	1	2	3	4
Input (Total)	1	0.9847	0.0041	0.0042	0.0070	1	0.9356	0.0018	0.0194	0.0432
	2	0.0040	0.9899	0.0029	0.0032	2	0.0231	0.9056	0.0390	0.0323
	3	0.0085	0.0070	0.9789	0.0056	3	0.0438	0.0288	0.8281	0.0992
	4	0.0076	0.0037	0.0044	0.9843	4	0.0708	0.0166	0.0376	0.8750
Realization 1	1	0.9868	0.0044	0.0003	0.0086	1	0.9315	0.0018	0.0021	0.0645
	2	0.0040	0.9861	0.0023	0.0076	2	0.0328	0.8928	0.0128	0.0617
	3	0.0048	0.0144	0.9647	0.0160	3	0.0025	0.0900	0.7373	0.1702
	4	0.0091	0.0057	0.0014	0.9838	4	0.0731	0.0309	0.0144	0.8816
Realization 3	1	0.9883	0.0050	0.0005	0.0061	1	0.9754	0.0025	0.0006	0.0216
	2	0.0032	0.9932	0.0017	0.0019	2	0.0259	0.9253	0.0104	0.0385
	3	0.0076	0.0265	0.9545	0.0114	3	0.0322	0.1610	0.7045	0.1023
	4	0.0072	0.0076	0.0004	0.9847	4	0.0869	0.0225	0.0066	0.8839
Realization 5	1	0.9918	0.0040	0.0006	0.0037	1	0.9789	0.0029	0.0041	0.0142
	2	0.0036	0.9950	0.0012	0.0002	2	0.0251	0.9451	0.0042	0.0256
	3	0.0436	0.0179	0.9231	0.0154	3	0.0897	0.1795	0.6821	0.0487
	4	0.0127	0.0104	0.0023	0.9746	4	0.1918	0.0018	0.0200	0.7864
Realization 7	1	0.9900	0.0047	0.0009	0.0044	1	0.9529	0.0015	0.0015	0.0442
	2	0.0028	0.9948	0.0010	0.0014	2	0.0170	0.9512	0.0141	0.0177
	3	0.0025	0.0301	0.9662	0.0013	3	0.0329	0.0868	0.7000	0.1803
	4	0.0103	0.0062	0.0021	0.9814	4	0.0937	0.0258	0.0003	0.8802

Table 5. Statistics of some Realizations using the total TPMs and different boundaries from observed transections

		Cell size in x-direction = 10m Cell size in y-direction = 5cm								
		TPM at x-direction				TPM at y-direction				
	State	1	2	3	4	State	1	2	3	4
Input (Total)	1	0.9847	0.0041	0.0042	0.0070	1	0.9356	0.0018	0.0194	0.0432
	2	0.0040	0.9899	0.0029	0.0032	2	0.0231	0.9056	0.0390	0.0323
	3	0.0085	0.0070	0.9789	0.0056	3	0.0438	0.0288	0.8281	0.0992
	4	0.0076	0.0037	0.0044	0.9843	4	0.0708	0.0166	0.0376	0.8750
Realization 2	1	0.9897	0.0020	0.0004	0.0079	1	0.9609	0.0010	0.0016	0.0366
	2	0.0039	0.9890	0.0048	0.0024	2	0.0112	0.8925	0.0157	0.0806

	3	0.0041	0.0165	0.9702	0.0091	3	0.0017	0.1893	0.7322	0.0769
	4	0.0063	0.0059	0.0010	0.9868	4	0.0974	0.0107	0.0129	0.8790
Realization 4	1	0.9838	0.0038	0.0023	0.0101	1	0.9171	0.0003	0.0026	0.0800
	2	0.0006	0.9944	0.0013	0.0038	2	0.0175	0.9401	0.0019	0.0405
	3	0.0057	0.0080	0.9543	0.0320	3	0.1566	0.0697	0.6834	0.0903
	4	0.0169	0.0051	0.0006	0.9773	4	0.0929	0.0216	0.0342	0.8513
Realization 6	1	0.9873	0.0035	0.0022	0.0070	1	0.9669	0.0016	0.0086	0.0230
	2	0.0013	0.9978	0.0004	0.0005	2	0.0134	0.9531	0.0076	0.0258
	3	0.0180	0.0114	0.9639	0.0066	3	0.1395	0.0028	0.7287	0.1290
	4	0.0120	0.0072	0.0021	0.9788	4	0.1159	0.0128	0.0232	0.8481
Realization 8	1	0.9858	0.0052	0.0020	0.0070	1	0.9365	0.0008	0.0011	0.0615
	2	0.0005	0.9967	0.0003	0.0025	2	0.0137	0.9522	0.0064	0.0277
	3	0.0028	0.0266	0.9692	0.0014	3	0.0783	0.0937	0.8084	0.0196
	4	0.0132	0.0139	0.0007	0.9722	4	0.1205	0.0686	0.0033	0.8076

4.2. Simulation of genetic soil transections

The layering of genetic soils is usually intrinsic with several genetic horizons from the surface to bottom in 1m or 2m depths, e.g. A1 (surface soil horizon), A2 (subsurface soil horizon), B (central soil horizon), and C (parent materials horizon) horizons. But the thickness of soil genetic horizons is still spatially variable at a regional scale.

We use hypothetical data to generate several realizations of genetic soil transections with 4 horizons and two depths (Fig.7). The input data and statistics of TPMs for realizations are shown in Table 6. Because transitions only occur between neighboring horizons, the transition probabilities between not neighboring horizons are always zero in TPMs. Results show that this method can basically describe the natural format of genetic soil transections. Related to the simulation direction, the borders between neighboring horizons, i.e. changes of horizontal thickness, show a saw-toothed shape.

Table 6. Statistics of some Realizations of genetic soil transections using different ideal TPMs and boundaries

		Cell size in x-direction = 10m Cell size in y-direction = 2cm								
		TPM at x-direction				TPM at y-direction				
	State	1	2	3	4	State	1	2	3	4
Input 1 (Ideal)	1	0.9500	0.0500	0.0000	0.0000	1	0.8000	0.2000	0.0000	0.0000
	2	0.0250	0.9500	0.0250	0.0000	2	0.0000	0.9000	0.1000	0.0000
	3	0.0000	0.0160	0.9700	0.0140	3	0.0000	0.0000	0.9333	0.0667
	4	0.0000	0.0000	0.0120	0.9880	4	0.0000	0.0000	0.0000	1.0000
Realization 1-1	1	0.9709	0.0291	0.0000	0.0000	1	0.7295	0.2705	0.0000	0.0000
	2	0.0100	0.9726	0.0174	0.0000	2	0.0000	0.9022	0.0978	0.0000
	3	0.0000	0.0125	0.9742	0.0133	3	0.0000	0.0000	0.9245	0.0755
	4	0.0000	0.0000	0.0090	0.9910	4	0.0000	0.0000	0.0000	1.0000
Realization 1-2	1	0.9681	0.0319	0.0000	0.0000	1	0.7545	0.2455	0.0000	0.0000
	2	0.0122	0.9722	0.0155	0.0000	2	0.0000	0.8985	0.1015	0.0000
	3	0.0000	0.0072	0.9844	0.0085	3	0.0000	0.0000	0.9582	0.0418

		4	0.0000	0.0000	0.0115	0.9885	4	0.0000	0.0000	0.0000	1.0000
		Cell size in x-direction = 10m				Cell size in y-direction = 5cm					
		TPM at x-direction				TPM at y-direction					
	State	1	2	3	4	State	1	2	3	4	
Input 2 (Ideal)	1	0.9534	0.0466	0.0000	0.0000	1	0.8757	0.1243	0.0000	0.0000	
	2	0.0676	0.8975	0.0349	0.0000	2	0.0000	0.8182	0.1818	0.0000	
	3	0.0000	0.0147	0.9755	0.0098	3	0.0000	0.0000	0.9201	0.0799	
	4	0.0000	0.0000	0.0079	0.9921	4	0.0000	0.0000	0.0000	1.0000	
Realization 2-1	1	0.9575	0.0425	0.0000	0.0000	1	0.8960	0.1040	0.0000	0.0000	
	2	0.0864	0.8736	0.0400	0.0000	2	0.0000	0.7894	0.2106	0.0000	
	3	0.0000	0.0110	0.9840	0.0050	3	0.0000	0.0000	0.9409	0.0591	
	4	0.0000	0.0000	0.0106	0.9894	4	0.0000	0.0000	0.0000	1.0000	
Realization 2-2	1	0.9557	0.0443	0.0000	0.0000	1	0.8984	0.1016	0.0000	0.0000	
	2	0.0887	0.8684	0.0428	0.0000	2	0.0000	0.7967	0.2033	0.0000	
	3	0.0000	0.0150	0.9782	0.0067	3	0.0000	0.0000	0.9310	0.0690	
	4	0.0000	0.0000	0.0086	0.9914	4	0.0000	0.0000	0.0000	1.0000	
Input 3 (Ideal)	State	1	2	3	4	State	1	2	3	4	
	1	0.9884	0.0116	0.0000	0.0000	1	0.8757	0.1243	0.0000	0.0000	
	2	0.0169	0.9657	0.0174	0.0000	2	0.0000	0.8182	0.1818	0.0000	
	3	0.0000	0.0073	0.9829	0.0098	3	0.0000	0.0000	0.9201	0.0799	
4	0.0000	0.0000	0.0079	0.9921	4	0.0000	0.0000	0.0000	1.0000		
Realization 3-1	1	0.9876	0.0124	0.0000	0.0000	1	0.8454	0.1546	0.0000	0.0000	
	2	0.0230	0.9649	0.0121	0.0000	2	0.0000	0.7447	0.2553	0.0000	
	3	0.0000	0.0034	0.9892	0.0074	3	0.0000	0.0000	0.9327	0.0673	
	4	0.0000	0.0000	0.0053	0.9947	4	0.0000	0.0000	0.0000	1.0000	
Realization 3-2	1	0.9855	0.0145	0.0000	0.0000	1	0.8775	0.1225	0.0000	0.0000	
	2	0.0289	0.9572	0.0139	0.0000	2	0.0000	0.7859	0.2141	0.0000	
	3	0.0000	0.0077	0.9820	0.0103	3	0.0000	0.0000	0.8972	0.1028	
	4	0.0000	0.0000	0.0056	0.9944	4	0.0000	0.0000	0.0000	1.0000	

4.3. Simulation of soil type map

We also try this method to simulate the surface spatial distribution of soil types - soil type map. A digital soil map, which has a length of 8km and a width of 6.2km, of a river basin in Belgium was selected for this purpose. We select only some parts of the map in which the soil types are distributed relatively homogeneously and combine the 41 soil types into a limited number of classes several ones to calculate parameters and conduct the simulation.

The simulation of a 4-type soil map with a length of 8km and a width of 3.5km is shown in Fig.8 and Table 7. The realizations with x' were simulated starting from the lower-left corner and their input TPM at y-direction was also counted from lower boundary to upper one. This results in an incline direction of soil type polygons in realization images contrary to the simulation starting from upper-left corner. The two types, Type 3 and Type 4, which occur very sparsely in the original map, can not be expressed in the simulated realizations. Type 4 is wetland. Obviously, its distribution is not statistically homogeneous or stationary. This does not fit that intrinsic assumption in the 2-D Markov chain process that the spatial change of states is a stationary process, i.e. a statistically homogeneous process. We can't get these true parameters reflecting the probabilistic law ruling the spatial distribution of soil types from this single sample.

Fig.9 and Table 8 show the simulation of an 8-type soil map with a length of 2.5km and a width of 1.5km. The simulated realizations can not also display the suitable proportion of different types very well as in the original map. The reason is similar to Fig. 8. The polygons of soil types are inclined with respect to the simulation direction.

From the digital soil type map (Fig. 10), we can see that the spatial distribution of soil types is not statistically homogeneous. We only can consider it as one single sample of the 2-D process of spatial changes of soil types. From such a sample, we can not get these parameters which can reflect the probabilistic law of the spatial process. To get suitable parameters, the statistical homogeneity or a lot of samples should be necessary.

Table 7. Statistics of some realizations using the TPMs and boundaries from digital soil map and different simulating directions

		Cell size in x-direction = 100m Cell size in y-direction = 100m								
		TPM at x-direction				TPM at y-direction				
	State	1	2	3	4	State	1	2	3	4
Input 1	1	0.7235	0.2246	0.0046	0.0473	1	0.7095	0.2428	0.0023	0.0454
	2	0.2475	0.7376	0.0041	0.0108	2	0.2464	0.7234	0.0084	0.0218
	3	0.2083	0.2500	0.5417	0.0000	3	0.4167	0.1250	0.3750	0.0833
	4	0.2802	0.0870	0.0000	0.6329	4	0.2917	0.0781	0.0000	0.6302
Realization 1	1	0.7370	0.2567	0.0000	0.0063	1	0.7432	0.2472	0.0000	0.0096
	2	0.2316	0.7663	0.0007	0.0014	2	0.2172	0.7814	0.0000	0.0014
	3	0.5000	0.0000	0.5000	0.0000	3	0.5000	0.5000	0.0000	0.0000
	4	0.6250	0.1250	0.0000	0.2500	4	0.8125	0.0625	0.0000	0.1250
Input 1'	1	0.7235	0.2246	0.0046	0.0473	1	0.7156	0.2322	0.0079	0.0442
	2	0.2475	0.7376	0.0041	0.0108	2	0.2603	0.7246	0.0025	0.0126
	3	0.2083	0.2500	0.5417	0.0000	3	0.1364	0.4545	0.4091	0.0000
	4	0.2802	0.0870	0.0000	0.6329	4	0.2802	0.1256	0.0097	0.5845
Realization 1'	1	0.7576	0.2332	0.0000	0.0092	1	0.7421	0.2536	0.0000	0.0043
	2	0.2626	0.7374	0.0000	0.0000	2	0.2772	0.7205	0.0000	0.0024
	3	0.0000	0.0000	0.0000	0.0000	3	0.0000	0.0000	0.0000	0.0000
	4	0.3571	0.1786	0.0000	0.4643	4	0.6071	0.2500	0.0000	0.1429
		Cell size in x-direction = 50m Cell size in y-direction = 50m								
		TPM at x-direction				TPM at y-direction				
	State	1	2	3	4	State	1	2	3	4
Input 2	1	0.8286	0.1367	0.0055	0.0292	1	0.8242	0.1439	0.0024	0.0295
	2	0.1576	0.8321	0.0024	0.0080	2	0.1555	0.8280	0.0054	0.0111
	3	0.1100	0.2600	0.6100	0.0200	3	0.2400	0.1300	0.5800	0.0500
	4	0.1705	0.0481	0.0000	0.7815	4	0.1617	0.0416	0.0012	0.7955
Realization 2	1	0.8677	0.1312	0.0000	0.0011	1	0.8652	0.1338	0.0000	0.0010
	2	0.1890	0.8107	0.0002	0.0000	2	0.1915	0.8076	0.0000	0.0009
	3	0.2500	0.0000	0.7500	0.0000	3	1.0000	0.0000	0.0000	0.0000
	4	0.5294	0.1176	0.0000	0.3529	4	0.4667	0.0667	0.0000	0.4667
	1	0.8286	0.1367	0.0055	0.0292	1	0.8265	0.1417	0.0048	0.0270

Input 2'	2	0.1576	0.8321	0.0024	0.0080	2	0.1588	0.8307	0.0028	0.0076
	3	0.1100	0.2600	0.6100	0.0200	3	0.1250	0.2604	0.6042	0.0104
	4	0.1705	0.0481	0.0000	0.7815	4	0.1705	0.0584	0.0057	0.7654
	1	0.8871	0.1111	0.0000	0.0018	1	0.8815	0.1165	0.0000	0.0019
Realization 2'	2	0.1976	0.8006	0.0000	0.0018	2	0.2037	0.7952	0.0000	0.0010
	3	0.0000	0.0000	0.0000	0.0000	3	0.0000	0.0000	0.0000	0.0000
	4	0.2239	0.1194	0.0000	0.6567	4	0.5538	0.1846	0.0000	0.2615
	1	0.8871	0.1111	0.0000	0.0018	1	0.8815	0.1165	0.0000	0.0019

Table 8. Statistics of some realizations using the TPMs and boundaries from digital soil map and different simulating directions

		Cell size in x-direction = 50m Cell size in y-direction = 50m								
		State	1	2	3	4	5	6	7	8
Input TPM at x-direction	1	0.7238	0.0000	0.1238	0.0952	0.0429	0.0000	0.0095	0.0048	
	2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
	3	0.1724	0.0000	0.7241	0.0069	0.0552	0.0069	0.0138	0.0207	
	4	0.0700	0.0000	0.0168	0.8291	0.0756	0.0000	0.0084	0.0000	
	5	0.0053	0.0000	0.0159	0.0584	0.7586	0.0875	0.0663	0.0080	
	6	0.0260	0.0000	0.0000	0.0325	0.1688	0.6883	0.0519	0.0325	
	7	0.0000	0.0000	0.0065	0.0000	0.1806	0.0710	0.7419	0.0000	
	8	0.0952	0.0000	0.1190	0.0000	0.0000	0.0714	0.0000	0.7143	
Input TPM at y-direction	1	0.6990	0.0000	0.0971	0.1456	0.0291	0.0000	0.0000	0.0291	
	2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
	3	0.2154	0.0000	0.6923	0.0154	0.0385	0.0077	0.0000	0.0308	
	4	0.0738	0.0000	0.0328	0.8197	0.0683	0.0055	0.0000	0.0000	
	5	0.0185	0.0000	0.0290	0.0660	0.7256	0.0765	0.0818	0.0026	
	6	0.0065	0.0000	0.0130	0.0000	0.1948	0.7078	0.0519	0.0260	
	7	0.0000	0.0000	0.0129	0.0129	0.2516	0.0710	0.6516	0.0000	
	8	0.0000	0.0000	0.0645	0.0000	0.0000	0.0645	0.0000	0.8710	
Realization 1 TPM at x-direction	1	0.7652	0.0000	0.0445	0.1377	0.0486	0.0000	0.0040	0.0000	
	2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
	3	0.2564	0.0000	0.5385	0.0769	0.1282	0.0000	0.0000	0.0000	
	4	0.0591	0.0000	0.0040	0.8763	0.0591	0.0000	0.0013	0.0000	
	5	0.0000	0.0000	0.0027	0.0885	0.8686	0.0268	0.0134	0.0000	
	6	0.0000	0.0000	0.0000	0.0000	0.7500	0.2500	0.0000	0.0000	
	7	0.0000	0.0000	0.0000	0.0000	0.2381	0.0952	0.6667	0.0000	
	8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
Realization 1 TPM at y-direction	1	0.6911	0.0000	0.0163	0.2724	0.0203	0.0000	0.0000	0.0000	
	2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
	3	0.5789	0.0000	0.2895	0.1053	0.0263	0.0000	0.0000	0.0000	
	4	0.0518	0.0000	0.0123	0.8649	0.0709	0.0000	0.0000	0.0000	
	5	0.0163	0.0000	0.0054	0.0840	0.8591	0.0244	0.0108	0.0000	
	6	0.1429	0.0000	0.0000	0.0000	0.4286	0.4286	0.0000	0.0000	
	7	0.0000	0.0000	0.0000	0.0476	0.8095	0.0476	0.0952	0.0000	
	8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	

	1	0.7531	0.0000	0.1111	0.0988	0.0165	0.0000	0.0206	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.2698	0.0000	0.6825	0.0159	0.0317	0.0000	0.0000	0.0000
Realization 2	4	0.0471	0.0000	0.0214	0.8244	0.1071	0.0000	0.0000	0.0000
TPM at x-direction	5	0.0000	0.0000	0.0018	0.0585	0.9068	0.0201	0.0128	0.0000
	6	0.0000	0.0000	0.0000	0.1429	0.5238	0.2857	0.0476	0.0000
	7	0.0000	0.0000	0.0000	0.0000	0.2500	0.1111	0.6389	0.0000
	8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

	1	0.7366	0.0000	0.0782	0.1770	0.0082	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.2966	0.0000	0.6271	0.0593	0.0169	0.0000	0.0000	0.0000
Realization 2	4	0.0354	0.0000	0.0398	0.8341	0.0907	0.0000	0.0000	0.0000
TPM at y-direction	5	0.0073	0.0000	0.0036	0.0617	0.8911	0.0254	0.0109	0.0000
	6	0.0000	0.0000	0.0000	0.0000	0.7143	0.2857	0.0000	0.0000
	7	0.0000	0.0000	0.0278	0.0000	0.5278	0.0278	0.4167	0.0000
	8	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

	1	0.7303	0.0000	0.0955	0.0730	0.0730	0.0000	0.0169	0.0112
	2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.2588	0.0000	0.6824	0.0000	0.0353	0.0000	0.0118	0.0118
Realization 3	4	0.0390	0.0000	0.0093	0.8627	0.0872	0.0000	0.0019	0.0000
TPM at x-direction	5	0.0000	0.0000	0.0000	0.0735	0.8746	0.0197	0.0323	0.0000
	6	0.0000	0.0000	0.0000	0.2105	0.2632	0.4737	0.0526	0.0000
	7	0.0000	0.0000	0.0000	0.0000	0.3684	0.0351	0.5965	0.0000
	8	0.2500	0.0000	0.5000	0.0000	0.0000	0.0000	0.0000	0.2500

	1	0.7029	0.0000	0.0571	0.1943	0.0400	0.0000	0.0000	0.0057
	2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.3059	0.0000	0.6235	0.0235	0.0353	0.0000	0.0000	0.0118
Realization 3	4	0.0301	0.0000	0.0132	0.8550	0.0979	0.0038	0.0000	0.0000
TPM at y-direction	5	0.0073	0.0000	0.0000	0.0878	0.8556	0.0201	0.0293	0.0000
	6	0.0000	0.0000	0.0000	0.0000	0.6364	0.3182	0.0455	0.0000
	7	0.0000	0.0000	0.0000	0.0000	0.5088	0.0351	0.4561	0.0000
	8	0.0000	0.0000	0.5000	0.0000	0.0000	0.0000	0.0000	0.5000

	1	0.7238	0.0000	0.1238	0.0952	0.0429	0.0000	0.0095	0.0048
	2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.1724	0.0000	0.7241	0.0069	0.0552	0.0069	0.0138	0.0207
Input'	4	0.0700	0.0000	0.0168	0.8291	0.0756	0.0000	0.0084	0.0000
TPM at x-direction	5	0.0053	0.0000	0.0159	0.0584	0.7586	0.0875	0.0663	0.0080
	6	0.0260	0.0000	0.0000	0.0325	0.1688	0.6883	0.0519	0.0325
	7	0.0000	0.0000	0.0065	0.0000	0.1806	0.0710	0.7419	0.0000
	8	0.0952	0.0000	0.1190	0.0000	0.0000	0.0714	0.0000	0.7143

	1	0.6957	0.0000	0.1353	0.1304	0.0338	0.0048	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.1439	0.0000	0.6475	0.0863	0.0791	0.0144	0.0144	0.0144
Input'	4	0.0836	0.0000	0.0056	0.8357	0.0696	0.0000	0.0056	0.0000
TPM at y-direction	5	0.0158	0.0000	0.0132	0.0658	0.7237	0.0789	0.1026	0.0000
	6	0.0000	0.0000	0.0065	0.0130	0.1883	0.7078	0.0714	0.0130

	7	0.0000	0.0000	0.0000	0.0000	0.2214	0.0571	0.7214	0.0000
	8	0.1429	0.0000	0.0952	0.0000	0.0238	0.0952	0.0000	0.6429
Realization 1' TPM at x-direction	1	0.6585	0.0000	0.0813	0.2114	0.0488	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.1884	0.0000	0.7246	0.0000	0.0580	0.0000	0.0145	0.0145
	4	0.0303	0.0000	0.0043	0.8761	0.0865	0.0000	0.0029	0.0000
	5	0.0067	0.0000	0.0089	0.0848	0.8371	0.0491	0.0134	0.0000
	6	0.0000	0.0000	0.0000	0.0000	0.3385	0.6154	0.0154	0.0308
	7	0.0000	0.0000	0.0000	0.0000	0.3571	0.2143	0.4286	0.0000
	8	0.0741	0.0000	0.0370	0.0000	0.0000	0.0000	0.0000	0.8889
Realization 1' TPM at y-direction	1	0.6000	0.0000	0.1000	0.2417	0.0583	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.2113	0.0000	0.4789	0.2113	0.0704	0.0141	0.0141	0.0000
	4	0.0373	0.0000	0.0030	0.8970	0.0612	0.0000	0.0015	0.0000
	5	0.0044	0.0000	0.0022	0.1060	0.8433	0.0287	0.0155	0.0000
	6	0.0000	0.0000	0.0000	0.0156	0.3281	0.6094	0.0469	0.0000
	7	0.0000	0.0000	0.0000	0.0000	0.6875	0.0625	0.2500	0.0000
	8	0.0000	0.0000	0.0000	0.0000	0.0000	0.4074	0.0000	0.5926
Realization 2' TPM at x-direction	1	0.6975	0.0000	0.0924	0.1681	0.0420	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.1368	0.0000	0.7895	0.0105	0.0526	0.0000	0.0000	0.0105
	4	0.0335	0.0000	0.0074	0.8268	0.1248	0.0000	0.0074	0.0000
	5	0.0016	0.0000	0.0032	0.0963	0.8668	0.0161	0.0128	0.0032
	6	0.0000	0.0000	0.0000	0.0909	0.3636	0.5000	0.0455	0.0000
	7	0.0000	0.0000	0.0625	0.0000	0.6875	0.0625	0.1875	0.0000
	8	0.0357	0.0000	0.0714	0.0000	0.0000	0.0000	0.0000	0.8929
Realization 2' TPM at y-direction	1	0.6583	0.0000	0.0667	0.1833	0.0917	0.0000	0.0000	0.0000
	2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	3	0.1224	0.0000	0.6327	0.1735	0.0612	0.0000	0.0102	0.0000
	4	0.0261	0.0000	0.0037	0.8489	0.1213	0.0000	0.0000	0.0000
	5	0.0050	0.0000	0.0066	0.0880	0.8738	0.0133	0.0133	0.0000
	6	0.0000	0.0000	0.0000	0.0952	0.4286	0.4286	0.0476	0.0000
	7	0.0000	0.0000	0.0000	0.0000	0.6250	0.0000	0.3750	0.0000
	8	0.0714	0.0000	0.0000	0.0000	0.1429	0.1786	0.0000	0.6071

4.4. Problems

It is clear that this method at present is not perfect. There are some key problems to be further studied. Several key problems are as follows:

(1) The simulated realizations can not suitably express these types which occur sparsely in the original. They usually are reduced. The basic reason is that the parameters calculated from the original can't reflect the true probabilistic law ruling the spatial changes of soil types, if some types are scarce. So the estimation of parameters is a key problem. Statistical homogeneity and sufficiency of data are necessary.

(2) Simulated stripes are inclined with respect to the simulation direction. This usually does not fit the anisotropy of spatial distribution of soil types.

(3) Simulated stripes of soil layers appear more connective than the inferred from observed profiles.

(4) Realizations do not honor the measured points, only can be conditioned on two neighboring boundaries. These problems also occur in some other similar or related methods more or less, e.g. stochastic rainfall simulation based on two-state Markov-chain process, geostatistical simulation.

5. Conclusion

A coupled Markov-chain method was used to stochastically simulate the spatial distribution of soil layers and types. Results show the simulation is not very satisfactory and there are some problems to be further studied. The simulation of transections of alluvial soils is basically feasible if soil texture is not divided into too many types. But the fact that simulated stripes are a little inclined keeps being a problem. The invented ideal data can roughly express the spatial distribution of genetic soils. Related to the simulation direction, the borders between neighboring horizons, i.e. changes of horizontal thickness, show a saw-toothed shape. The estimation of parameters will be a key step in the simulation of soil maps using this method. The types sparsely occurred in the sampled original can not be suitably expressed in the simulated realizations. The basic reason is that the parameters calculated from the original can't reflect the true probabilistic law ruling the spatial changes of soil types, if some types are scarce. To get suitable parameters, the statistical homogeneity or a lot of samples should be necessary.

Although this method is not perfect at present, we think a potential application is prospective in the future with its further development because of its simplicity and clarity.

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References

- Elfeki, A.M. 1996: Stochastic characterization of geological heterogeneity and its impact on groundwater contaminant transport. Ph.D. Thesis of Delft University of Technology, The Netherlands
- Harbaugh, J.W., and Bonham-Carter, G.F. 1980: Computer simulation in geology. 55-97, Wiley-Interscience, New York
- Harbaugh, J.W. and Merriam, D.F. 1968: Computer applications in stratigraphic analysis. John Wiley & Son, New York
- Krumbein, W.C. 1968: Statistical models in sedimentology. *Sedimentology*, 10: 7-23
- Li, W. 1995: Stochastic simulation of soil profiles in a region and its application in researching into soil water balance. Ph.D. dissertation, Beijing Agricultural University (in Chinese)
- Li, W., Li, B., Shi, Y. and Tang, D. 1997: Application of Markov chain theory to describe the spatial distribution of textural layers. *Soil Sci.*, 162(9): 672-683
- Li, W., Li, B. and Shi, Y. 1999: Markov-chain simulation of soil textural profiles. *Geoderma*, (in press)

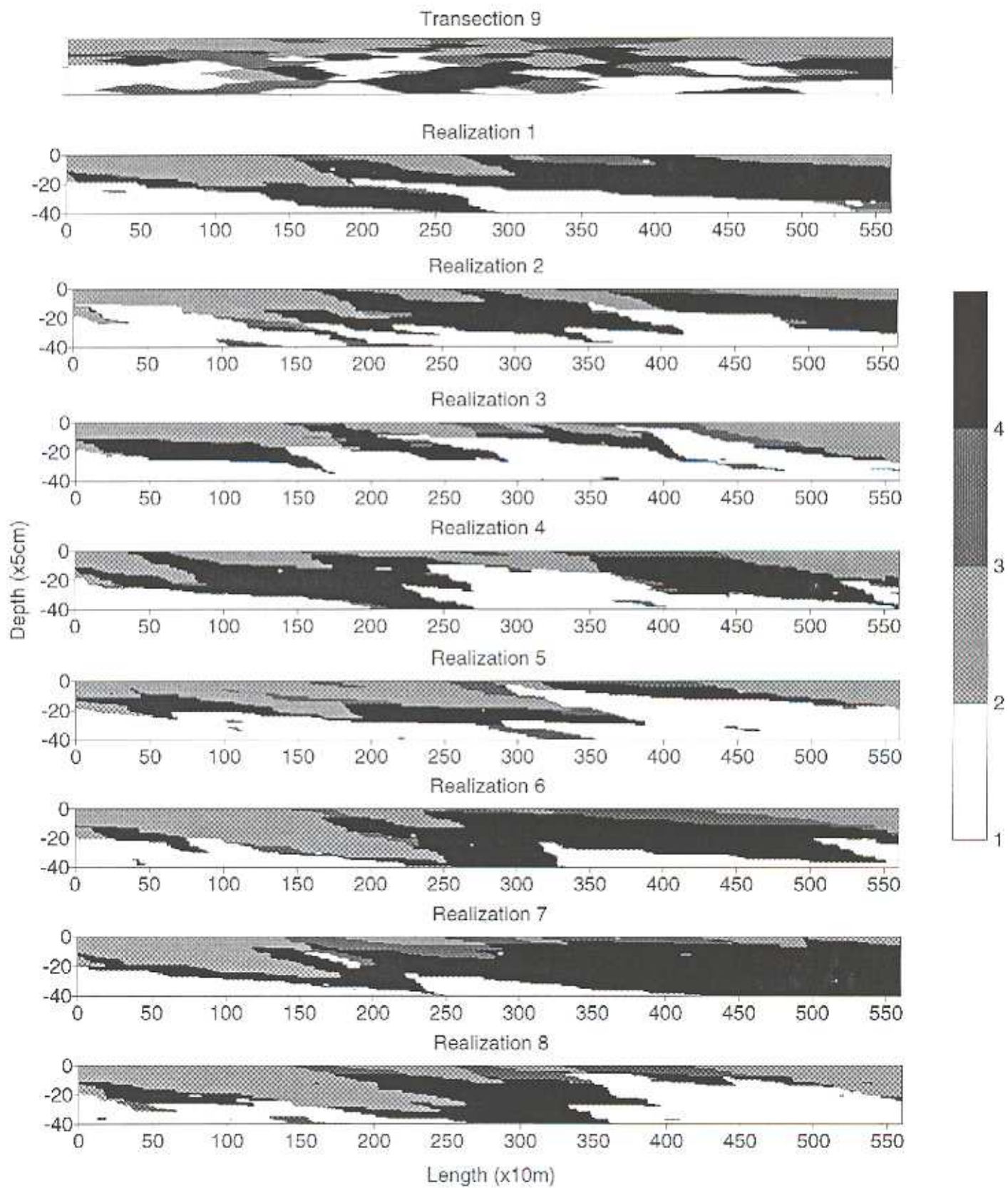


Fig. 2. Transection 9 and its 8 realizations

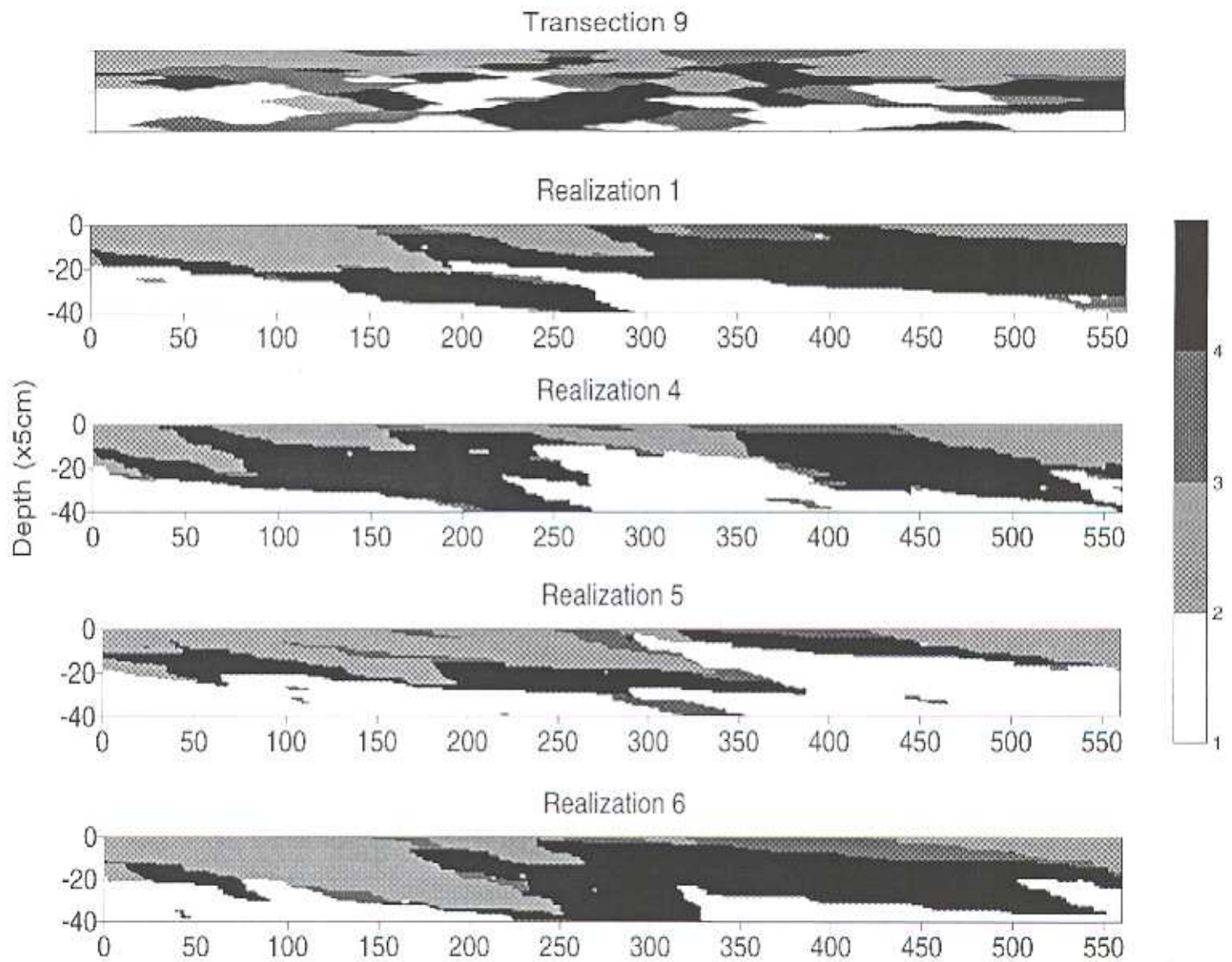


Fig. 2. Transection 9 and its some realizations

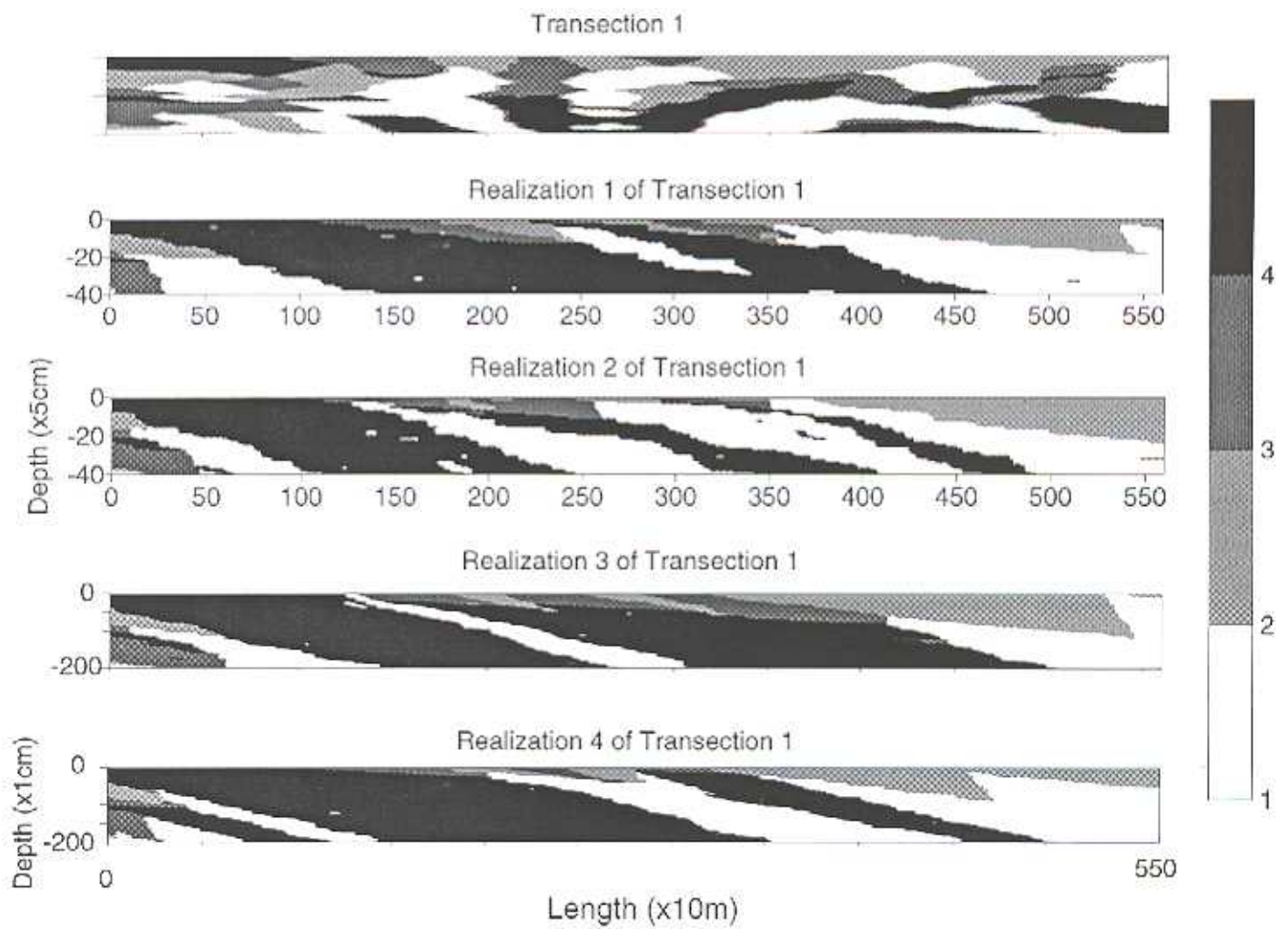


Fig. 3-1 Several realizations of Transection 1 with different grid cell sizes

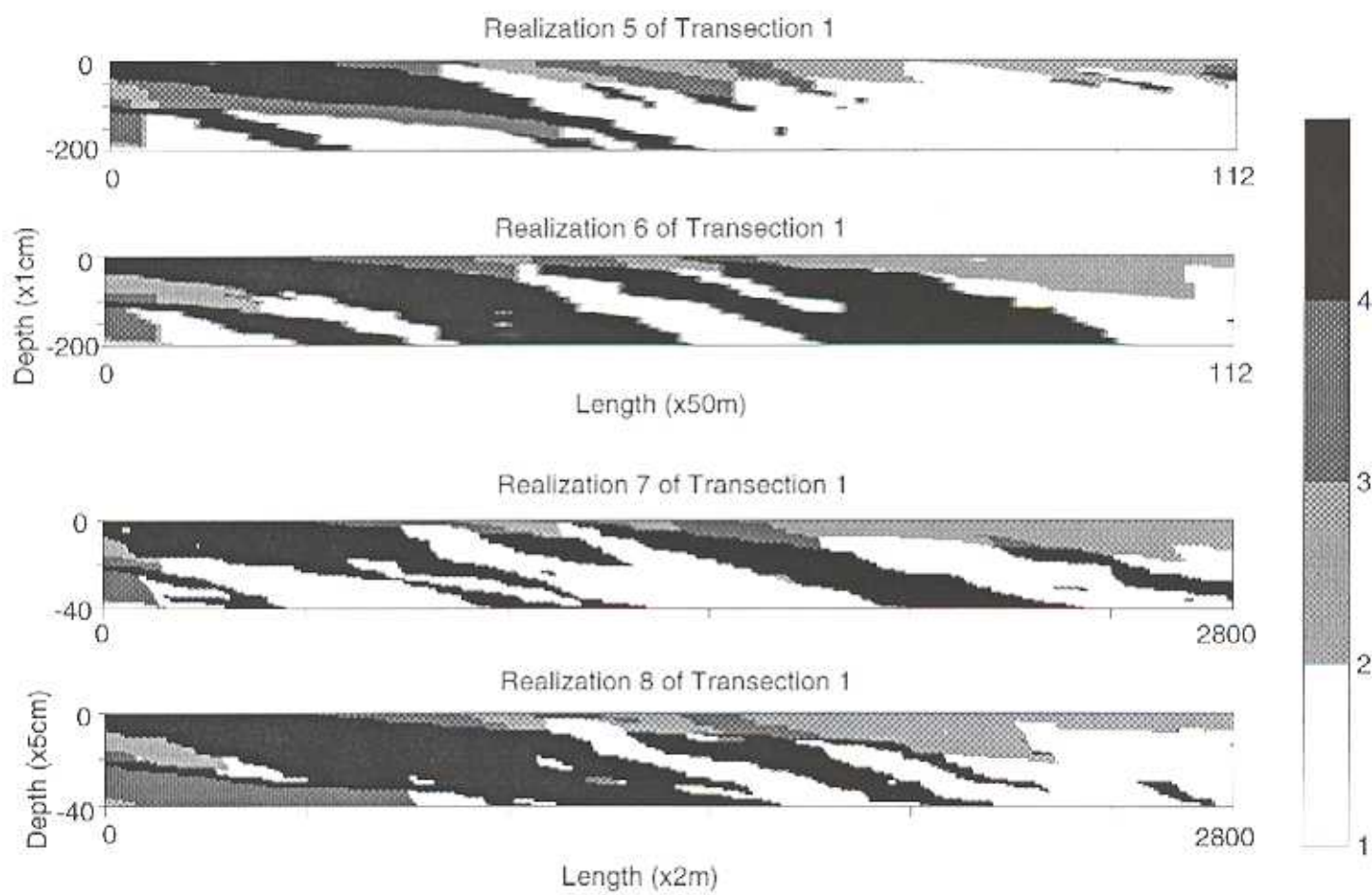


Fig. 3-2. Some realizations of Transection 1 with different grid cell sizes

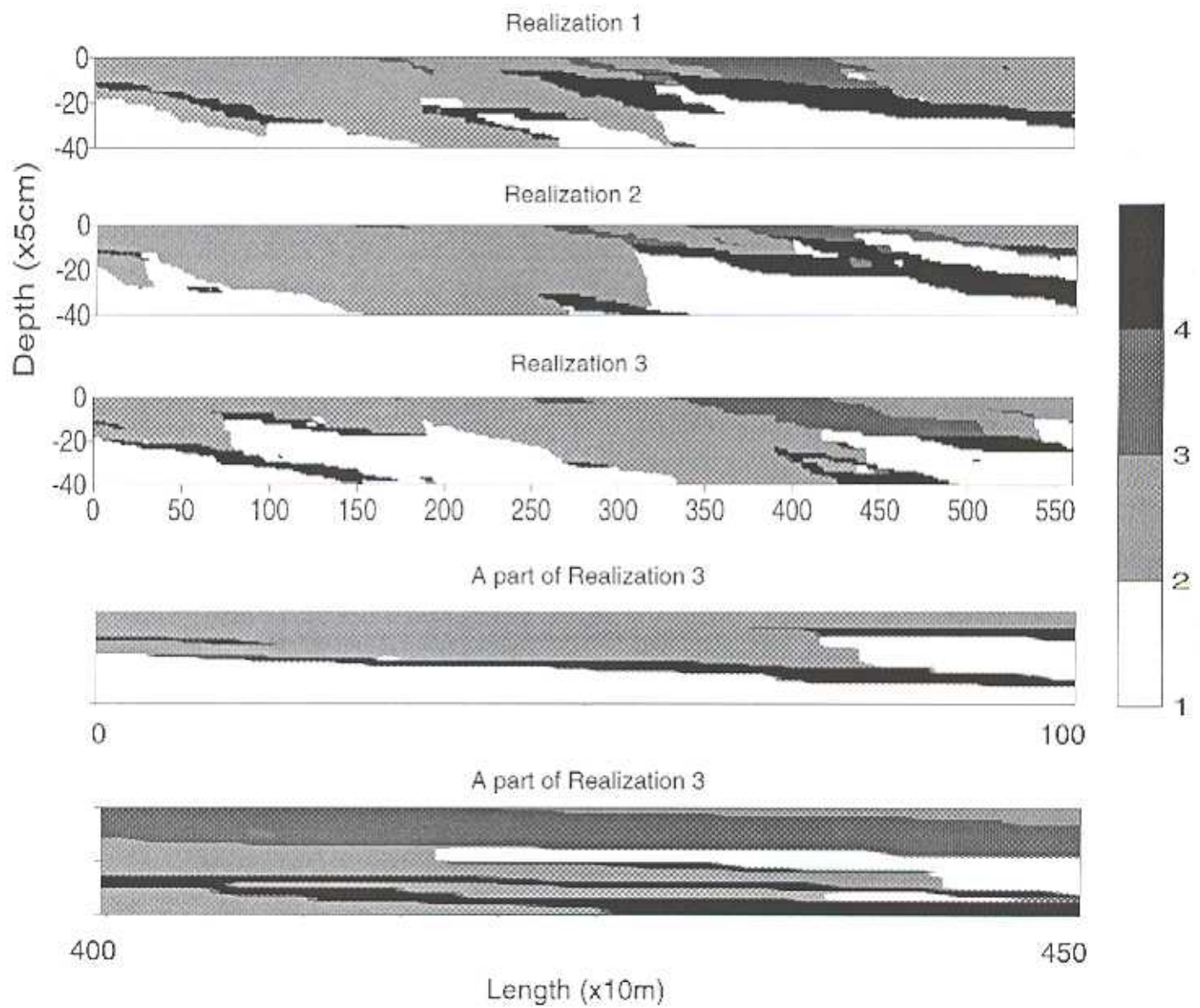


Fig. 4. Several simulated realizations based on total TPMs and boundaries of Transection 9

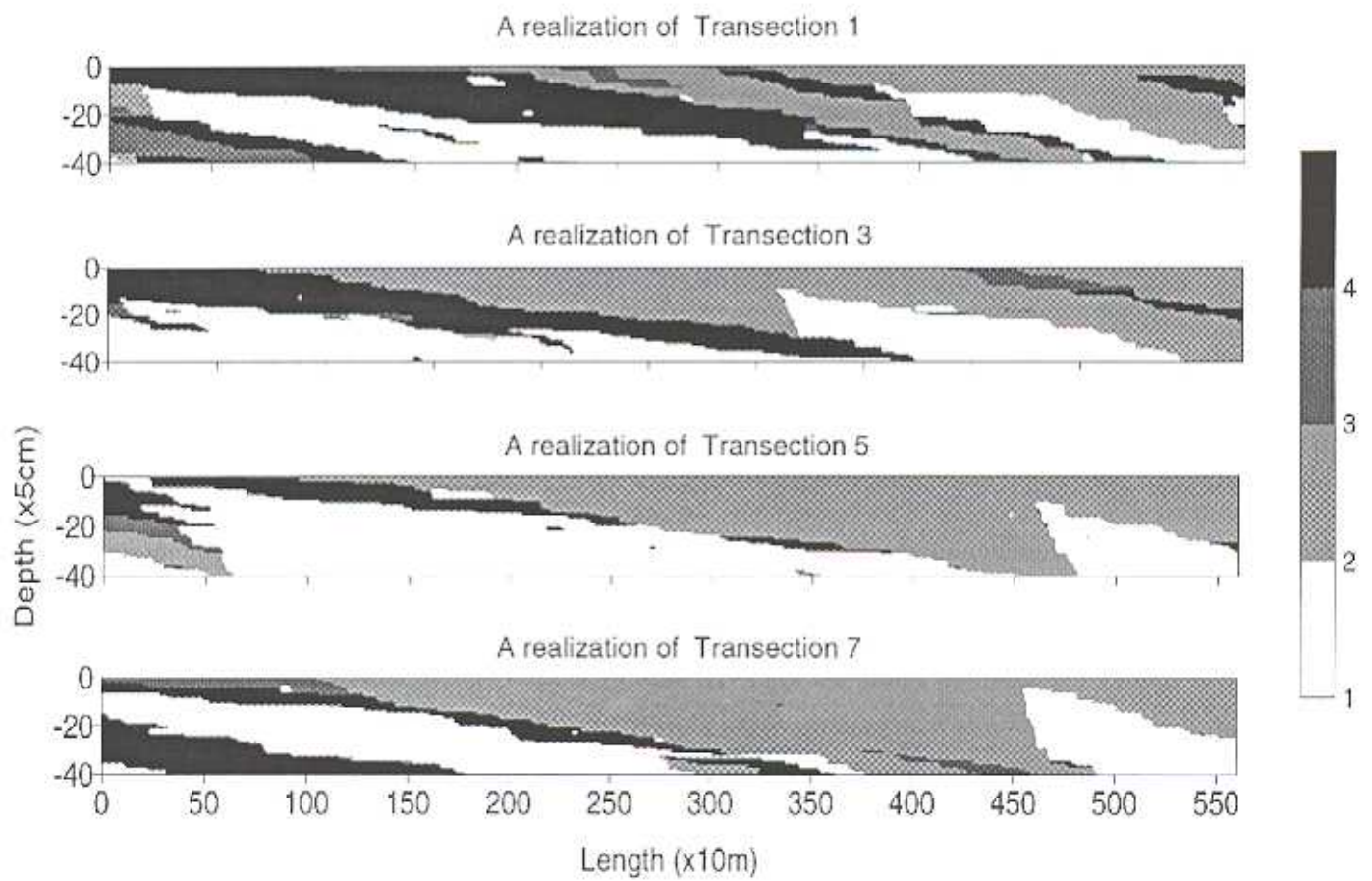


Fig. 5. Some simulated realizations of soil textural transections based on total TPMs and different boundaries from observed transections in an alluvial soil region

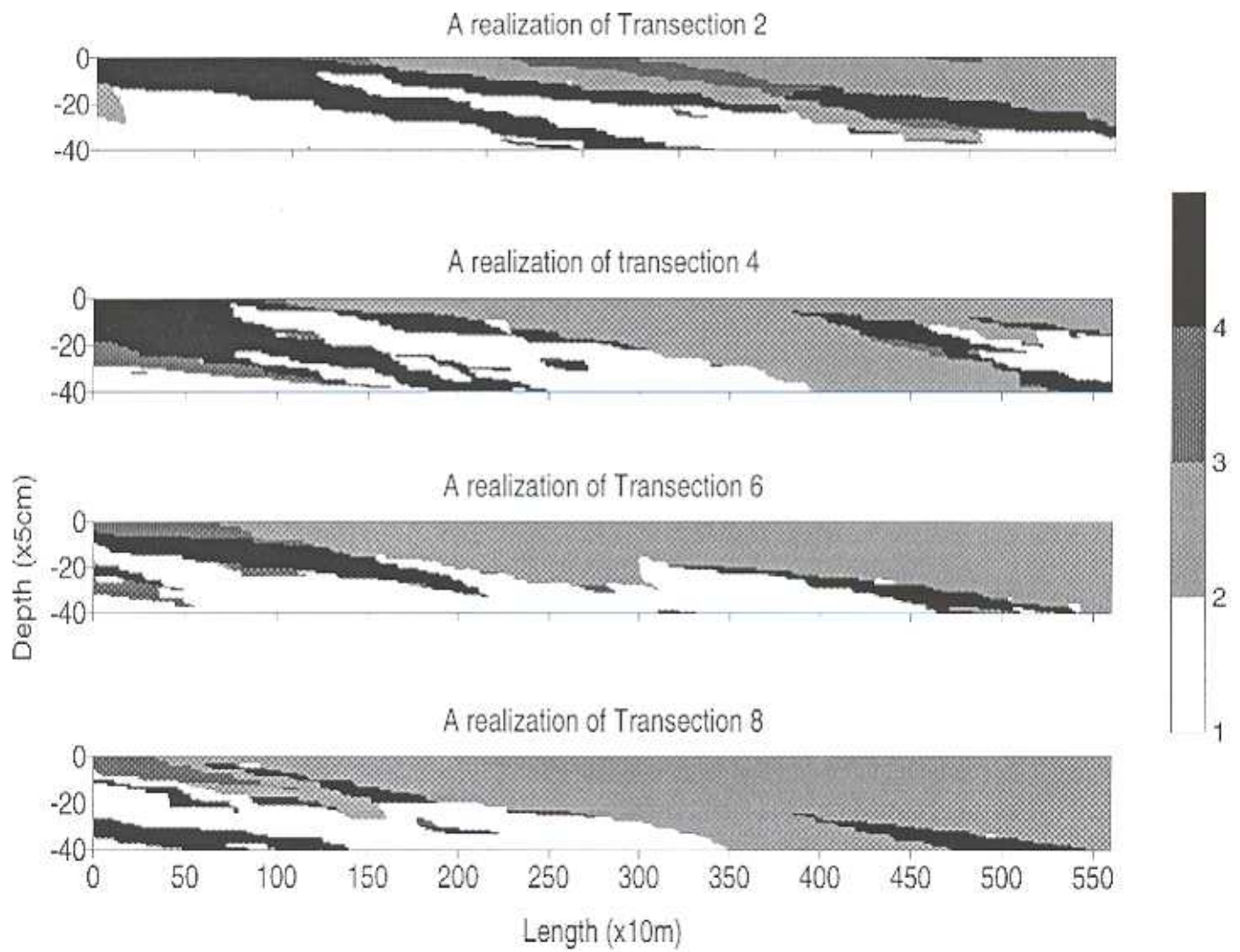


Fig. 6. Some simulated realizations of soil transections based on total TPMs and different boundaries from observed transections in an alluvial soil region

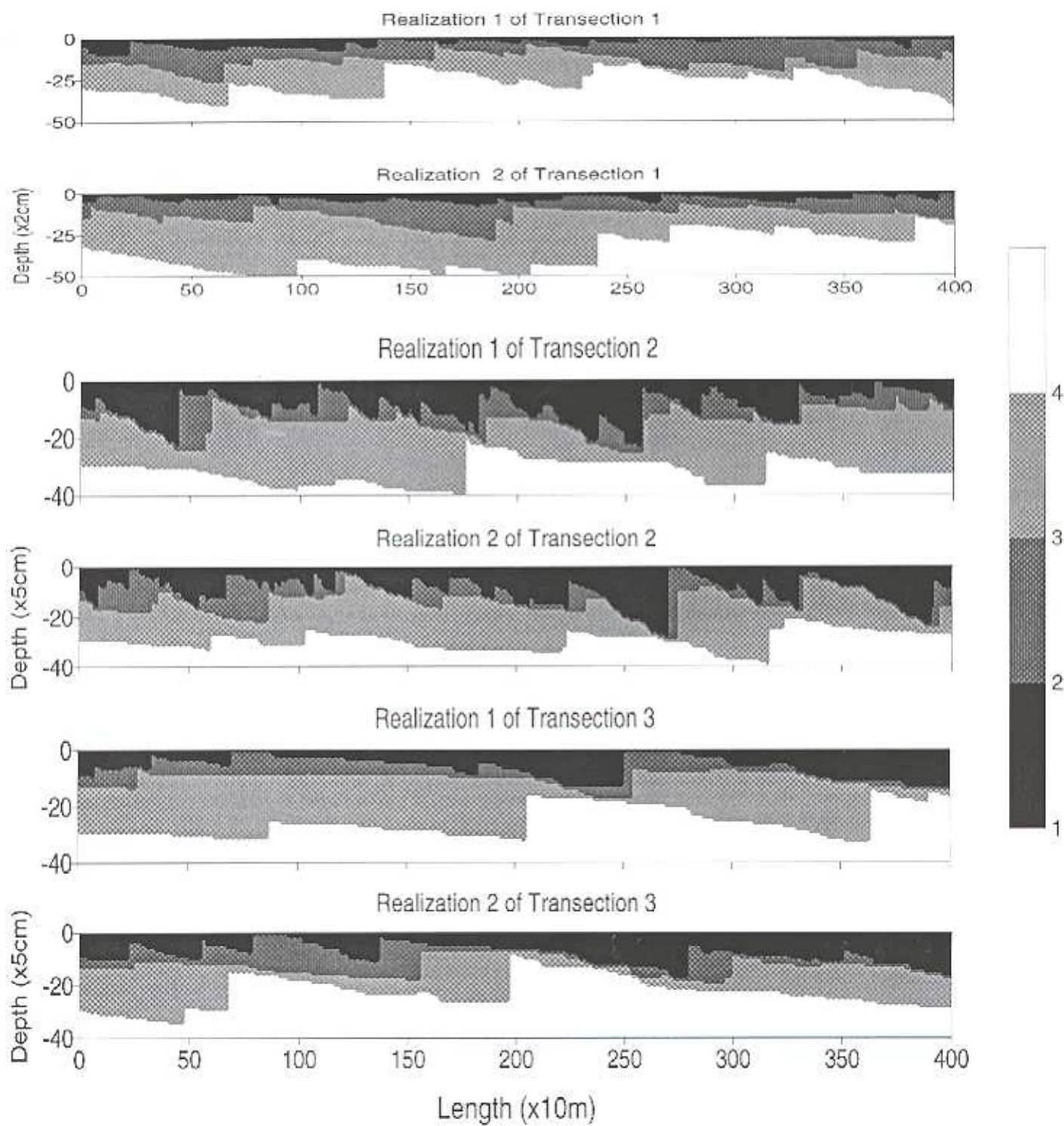


Fig. 7. Several simulated realizations of genetic soil transections based on ideal data and different boundaries

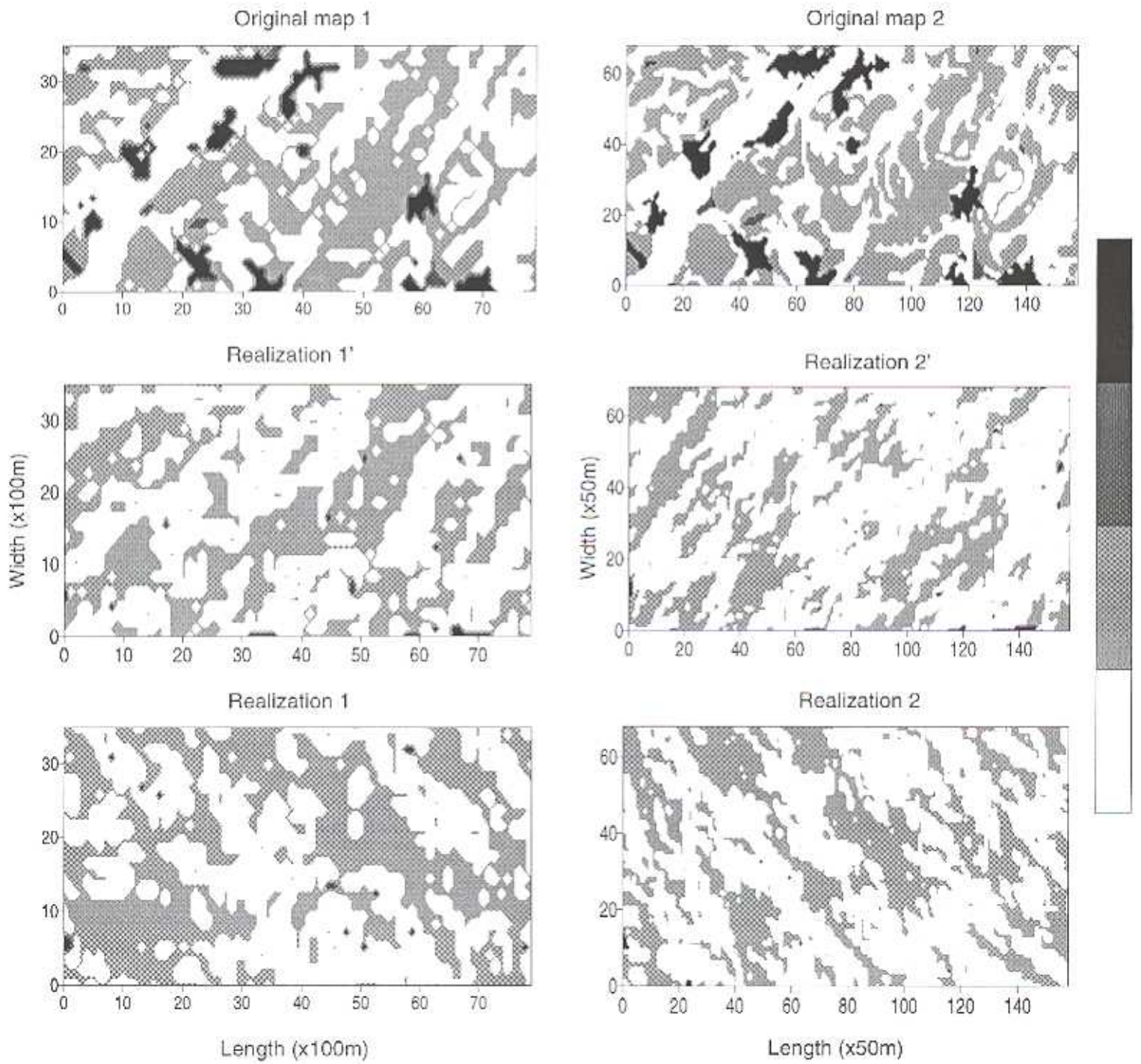


Fig. 8. Some conditional realizations of a digital soil map with different grid cell sizes and simulating directions

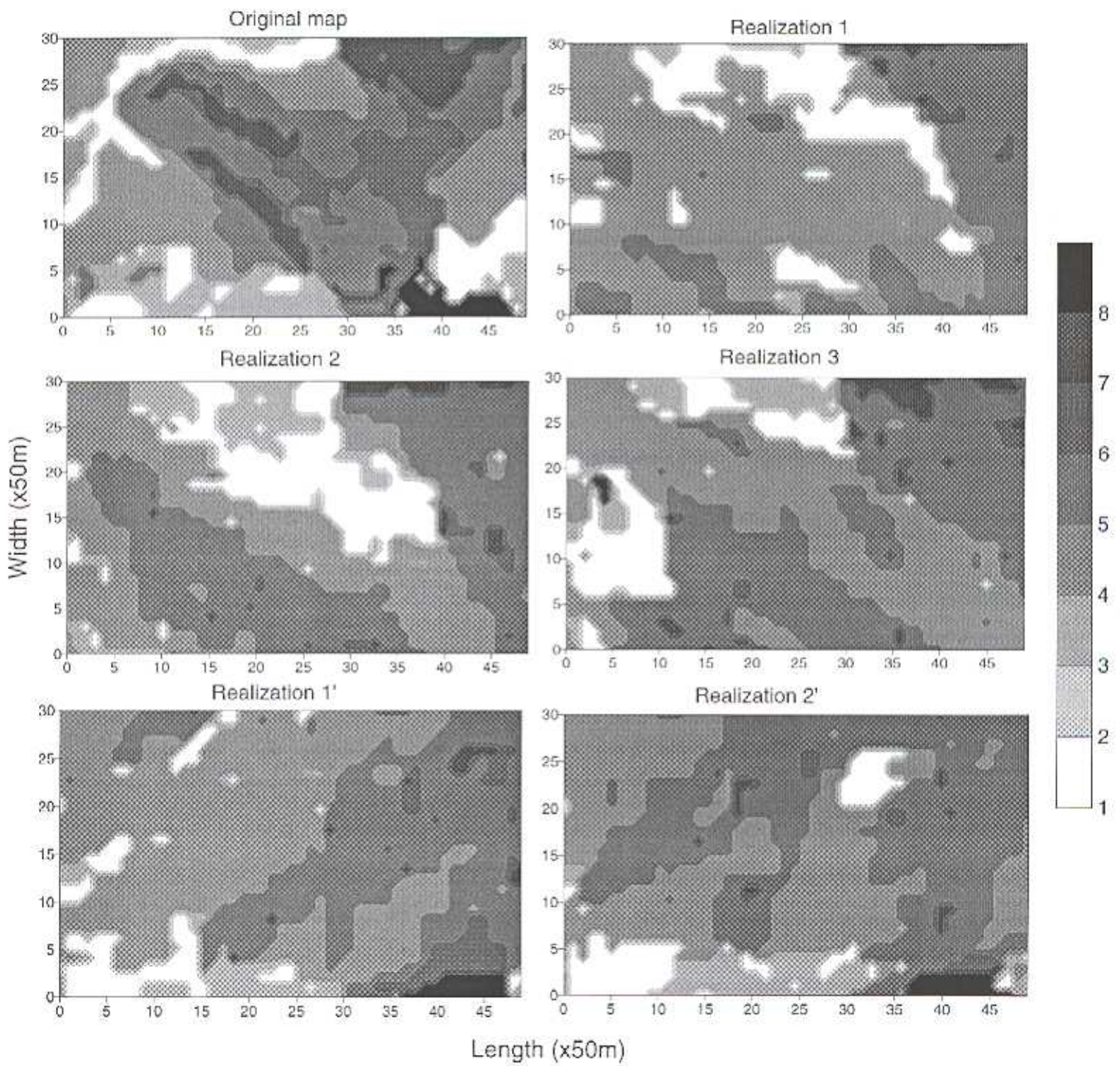


Fig. 9. Some conditional realizations of a digital soil map with different simulating directions

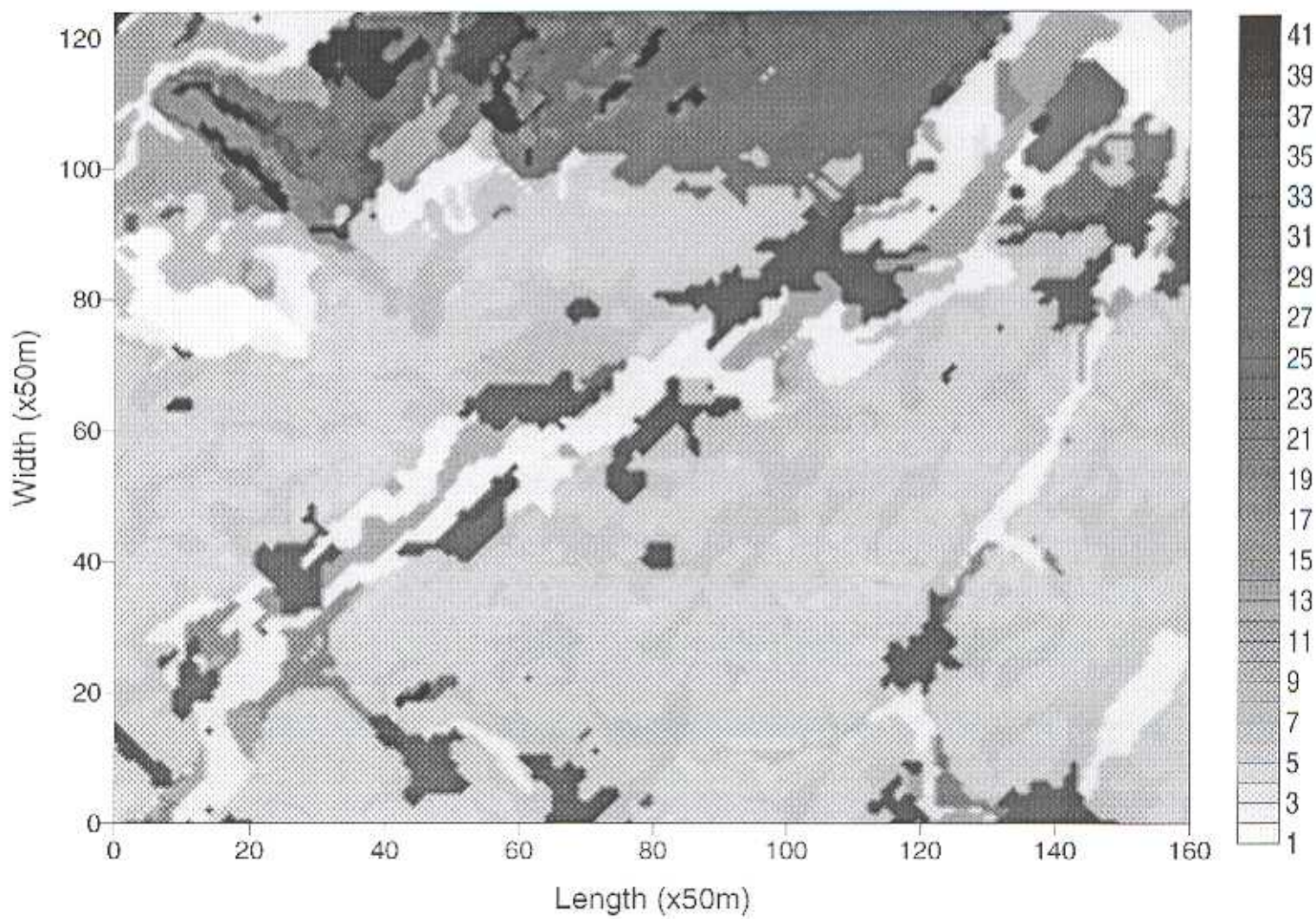


Fig. 10. A digital soil map with 41 soil types