УДК 004.048

QUALITATIVE MODELING OF TREES CULTIVATED WITH PROCESSED WASTEWATER

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Культивація лісових дерев обробленими стічними водами є ефективним методом зменшення викидів шкідливих речовин. Для цього проводяться детальні експерименти з вивчення здатності дерев поглинати хімічні елементи при підвищених концентраціях у стічних водах. В роботі розглядається розробка якісних інструментів моделювання для підтримки цього процесу вивчення. Система якісного виведення забезпечує дослідника якісними інструментами, показуючи складні взаємодії прозоро.

Ключові слова: *лісові дерева, екологічні мережі, якісне моделювання*.

Cultivation of forest trees with processed wastewater is an effective method to reduce the release of harmful substances. For this purpose, the detailed experiments shall be carried out to investigate the ability of trees to absorb chemical elements under increased concentrations in wastewater. The paper considers the development of qualitative modeling tools to support the investigation process. A qualitative inference system shall provide the investigator with qualitative tools showing the complex interactions in a transparent way.

Key words: forest trees, ecological networks, qualitative modeling.

Культивация лесных деревьев обработанными сточными водами является эффективным методом уменьшения выбросов вредных веществ. Для этого проводятся детальные эксперименты по изучению способности деревьев поглощать химические элементы при повышенных концентрациях в сточных водах. В работе рассматривается разработка качественных инструментов моделирования для поддержки этого процесса изучения. Система качественного вывода обеспечивает исследователя качественными инструментами, показывая сложные взаимодействия прозрачно.

Ключевые слова: *лесные деревья, экологические сети, качественное моделирования*.

Introduction

Wide utilization of wastewater and sludge for agricultural purposes requires a thorough investigation of the behavior of various trees in biological, chemical, and physical aspects under different wastewater supply conditions. The problem involves many factors and parameters, such as the impacts of treatments on soil and flora, survival and mortality rates of trees, their growth, silvicultural issues (roots and crown development, competition), wood properties, assimilation behavior for different chemical elements, etc. [1, 2, 3].

The investigation problem of cultivating the trees under wastewater supply has the following features:

- experiments shall be conducted under a long-term program with the extension of number of investigated trees in different areas;

- behavior and properties of the trees grown under wastewater supply conditions are the result of various cause-effect dynamical interactions in ecological networks, for which mathematical models of underlying processes are unknown [4];

- criteria of a “good” solution, which would clearly identify all aspects of the problem, are ill-defined, often contradictory, and cannot be formally stated;

- search within some model for a “good” solution is being carried out in multidimensional solution space under uncertainty conditions.

In this paper, a solution is proposed to the development of computer-based tools intended for the empirical modeling of trees behavior and qualitative reasoning [5] with imprecise information about this behavior.

Model analysis

As an example, let the concentrations of chemical elements in the leaves of different forest trees were measured during their cultivation with processed waste and irrigation water. Also, four water supply cases were applied for three tree species (combinations of processed wastewater, irrigation water, and sludge).

Measured concentrations were averaged for every group of trees and their parts (leaves, roots), and represented in the form of plots as functions $f_i : \mathbf{C}_i^W \to \mathbf{C}_i^M$ for heavy metal $e_i \in \{Cu^{++}, Mn^{++}, Zn^{++}, ...\}$, $\boldsymbol{C}^W$ and $\boldsymbol{C}^M$ - concentrations in water and in parts of trees respectively**.** Below the following notations will be used: *W* - set of water supply cases; *S* - set of trees; *M* - set of measured parts of trees; *E* - set of heavy metals (in general, chemical elements); ***C*** - vector (in general, ordered set) of real values of measured concentrations.

As an example, for a given set of experiments we have:

- $W=\{w_1,w_2,w_3\}$, where w_1 is processed wastewater; w_2 - irrigation water; w_3 - irrigation water with added heavy metals;

- $S=\{s_1,s_2,s_3\}$ - set of trees;

- $M=\{m_1,m_2\}$, m_1 - leaves; m_2 - roots;

- $E=\{e_1,e_2,e_3\}$, e_1 - Cu; e_2 - Mn; e_3 - Zn.

The relationships between interacting objects can be represented as the following chain:

$$\mathbf{C}^W(E) \to S \to \mathbf{C}^S(E)\,. \tag{1}$$

The task is to determine the reaction of trees by estimating $\boldsymbol{C}^S$ and by matching the pair ($\boldsymbol{C}^W$, $\boldsymbol{C}^S$). The estimation of $\boldsymbol{C}^S$ consists in the determination of whether the values of concentrations hold within admissible limits, how high/low is the concentration and its rate of change in whole within some range of values. When matching ($\boldsymbol{C}^W$, $\boldsymbol{C}^S$), the main focus is made on how significantly they differ from each other by values and rates of change.

The ecological chain of cause-effect interactions can be represented as follows:

$$W \to \mathbf{C}^W(E) \to S \to M \to \mathbf{C}^M(E). \tag{2}$$

This chain allows the investigator to provide more detailed analysis of trees behavior due to more detailed structure as to compare with relationships (1). Thus, analysis of the concentrations in roots and leaves and their matching gives additional information about peculiarities of biological processes inherent in different trees. Because the objective within the chain of relationships (2) is to estimate and analyze the functional relationship between $\boldsymbol{C}^W$ and $\boldsymbol{C}^M$, relationships (2) can be represented in the following form:

$$\mathbf{C}^W(E) \xrightarrow{W,S,M} \mathbf{C}^M(E), \tag{3}$$

where sets *W*, *S*, and *M* are the sets of cases for which the function is estimated.

During long-term investigations of complex ecological interaction networks, the model gradually extends and becomes more detailed, and one of the reasons of such extension is an attempt to explain unclear points in a trees' behavior. Unpredictable behavior arises due to lack of knowledge within some model, or if the model itself is not sufficiently adequate to take into account some important factors influencing on the behavior.

At the same time, as the chain extends, its analysis becomes more complicated. Let, for example, the measurements of concentrations of heavy metals in soil *G* under the trees be included in the model:

$$W \to \mathbf{C}^W(E) \to G \to \mathbf{C}^G(E) \to S \to M \to \mathbf{C}^M(E). \tag{4}$$

Now, the concentrations *E* in water *W* may be considered as factors that make an influence on *S* through the soil characteristics and thus, ensure mode deep and adequate view on the processes developed around investigated objects *S*.

Ecological chain as a chain of binary mappings

The relationships (1)-(4) of ecological chains can be considered as models that reflect an understanding of the problem at some stage of investigation and are *a priory* knowledge before a series of experiments starts. Further, the experiments are directed toward the estimation of unknown functional relationships within a given structure of the model, and the interpretation of obtained results.

The ecological chain (2) may be represented as a chain of binary mappings between each pair of its adjacent sets (Figure 1). One way from an object of the initial set W to an object of the end set E represents a minimal "cut" of functional relationship with single objects from W, E, S, M, and may be represented by the plot ($\boldsymbol{C}^W$, $\boldsymbol{C}^M$). In ultimate case, all possible ways after their empirical estimation cover a solution space within a given structure of the model. In principle, it would be enough to make some "good" clusterization of such a space to estimate a distribution of the ways on $\boldsymbol{C}^M$ for the function (3). In practice, however, the investigator iteratively makes cuts with different capacities by fixating subsets of the objects of interest, i.e., by selecting subsets of ways in the chain of binary mappings.

Let us consider the examples of such selection taken from the conclusions derived on the basis of experiments for the chain (2).

Example 1: Under wastewater (w_1), the concentrations of all metals (E) in leaves (m_1) and roots (m_2) *slightly increase* (for all trees).

Without an assessment of "slightly increase", the relevant variant of the chain (2) has the following form:

$$\{w_1\} \to E \to S \to M \to E, \qquad (5)$$

where subset of mappings is obtained by reducing W to single object w_1.

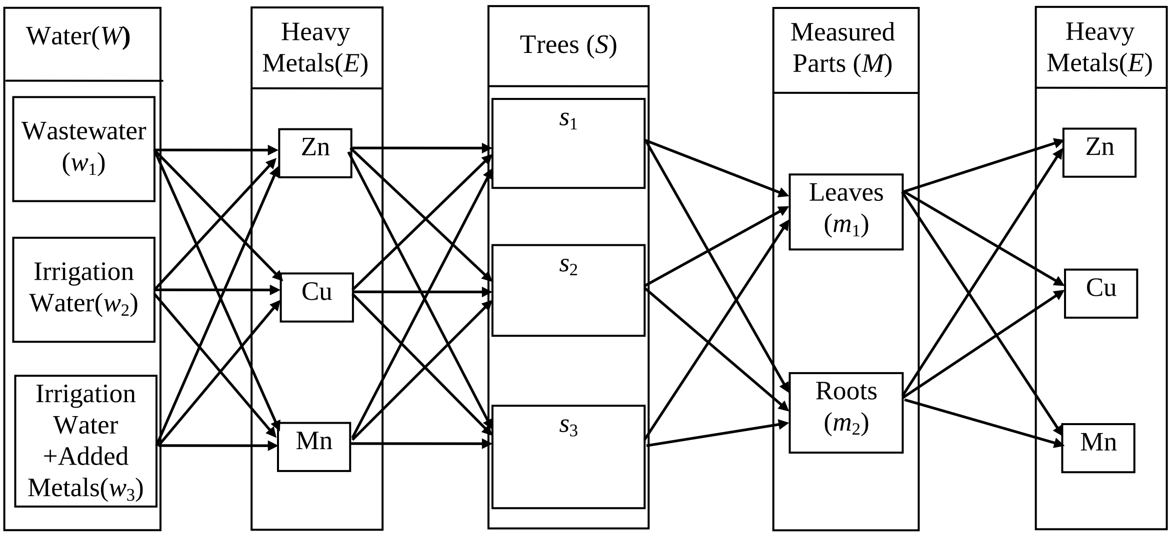

Fig. 1 Binary mappings for the chain (2)

Example 2: Irrigation with *high* concentrations (w_3) of Cu^{++}, Mn^{++}, and Zn^{++}(E) resulted to *significantly higher* concentrations of the metals in the roots (m_2) *than* in leaves (m_1):

$$[\{w_3\} \rightarrow E \rightarrow S \rightarrow \{m_1\} \rightarrow E] \Leftrightarrow [\{w_3\} \rightarrow E \rightarrow S \rightarrow \{m_2\} \rightarrow E],$$

or more briefly:

$$\{w_3\} \rightarrow E \rightarrow S \rightarrow [\{m_1 \Leftrightarrow m_2\}] \rightarrow E, \quad (6)$$

where the sign $\Leftrightarrow$ denotes matching two cases.

Example 3: Under irrigation with *high* concentrations (w_3), for trees (S) except (s_3), there is a *tolerance* in leaves (m_1) for all heavy metals (E):

$$\{w_3\} \rightarrow E \rightarrow [\{s_1, s_2\} \Leftrightarrow \{s_3\}] \rightarrow \{m_1\} \rightarrow E. \quad (7)$$

Example 4: Under *increased* concentrations of heavy metals in irrigation water (w_3), (s_2) absorbs Cu^{++} and Zn^{++} in the leaves (m_1) at *much higher* quantities *than* the other trees:

$$\{w_3\} \rightarrow \{Cu, Zn\} \rightarrow [\{s_2\} \Leftrightarrow \{s_1, s_3\}] \rightarrow \{m_1\} \rightarrow \{Cu, Zn\}. \quad (8)$$

Example 5: For the *increased* concentrations of metals (E) in irrigation water (w_3), the roots (m_2) absorb *high* concentrations in all trees (S):

$$\{w_3\} \rightarrow E \rightarrow S \rightarrow \{m_2\} \rightarrow E. \quad (9)$$

Example 6: In case of w_3, the concentration of Cu^{++} in the roots (m_2) of (s_2), when *the highest* concentration of Cu^{++} was applied in w_3, *increased dramatically* in relation to the other trees $\{s_1,s_3\}$:

$$\{w_3\} \rightarrow \{Cu\} \rightarrow [\{s_2\} \Leftrightarrow \{s_1, s_3\}] \rightarrow \{m_2\} \rightarrow \{Cu\}. \quad (10)$$

These examples show that the investigator should have the possibility to control the mappings by reducing the number of objects and factors under consideration, i.e., selecting a subset of possible ways in the interaction network. Thus, in the example 3 above, the analysis of the function $f: \mathbf{C}^W \rightarrow \mathbf{C}^M$ is reduced to the cases w_3 and m_1, and attention is focused on the objects from S, namely, how the trees behave and differ from each other by concentrations in leaves under the irrigation water with increased concentrations:

$$\{w_3\} \rightarrow E \rightarrow \overset{?}{S} \rightarrow \{m_1\} \rightarrow E. \quad (11)$$

Analysis of qualitative reasoning about function obtained from empirical results.

Qualitative knowledge derived from empirical data is virtually a description of solution space with substantially reduced dimensionality. Qualitative knowledge plays role of a skeleton to provide integral picture of multifactor environment at any investigation step, and to concentrate other information for the regions of space of special interest.

Recall that for the chain (2) there is an interest to estimate the function (3) between the concentrations of heavy metals in supplied water and in the parts of trees. Here, for each element from *E*, there is a real-value line $\boldsymbol{C}$ on which discrete values of concentrations are empirically obtained. Then each measurement made for the estimation of function $f:\mathbf{C}^W \to \mathbf{C}^M$ can be represented as a way between two real-value lines $\boldsymbol{C}^W$ and $\boldsymbol{C}^M$ through the sets *W*, *S*, and *M* involved in the chain. In Figure 2, an example is shown of empirical estimation for one heavy metal. One way reflects one measured point on the plot ($\boldsymbol{C}^W$, $\boldsymbol{C}^M$) for given objects from *W*, *S*, and *M*. The plot in whole is a subset of ways selected under the conditions that measured points on $\boldsymbol{C}^W$ are ordered within a given range. As can be seen from Figure 2, output concentrations $\boldsymbol{C}^M$ have different distributions depending of mapping cases, ($m_1 \vee m_2$) or m_1, with their own qualitative estimations.

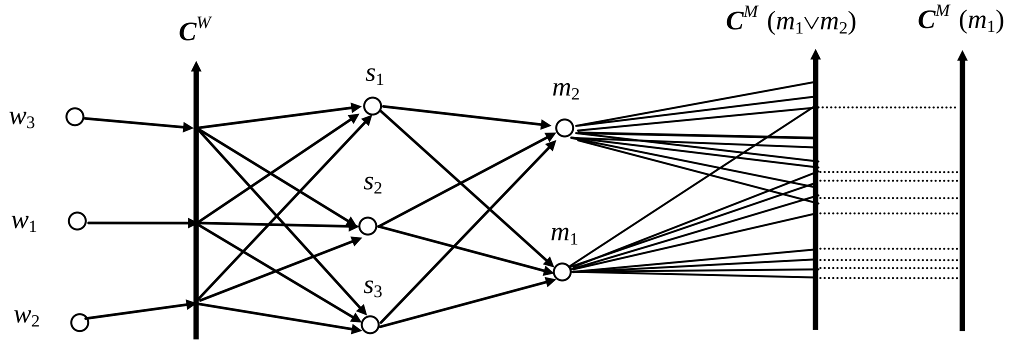

Figure 2. Estimation of f:$\boldsymbol{C}^W \to \boldsymbol{C}^M$ by mappings through *W*, *S*, *M*.

All the above examples of conclusions include such characteristics as “high”, “higher”, “highest”, “increase”, “slight increase”, “dramatically increased”, and others, by means of which the investigator qualitatively estimate the function $f:\mathbf{C}^W \to \mathbf{C}^M$. Therefore, it is reasonable to use the concept of qualitative sets[12] and assign to $\boldsymbol{C}^W$ and $\boldsymbol{C}^M$ some qualitative variables $Q_x=\{q^{(x)}{}_i\}$, $i=1,...,n_1$, and $Q_y=\{q^{(y)}{}_j\}$, $j=1,...,n_2$. Here, $q^{(x)}{}_i$ and $q^{(y)}{}_j$ are qualitative values with overlapping membership functions that reflect some qualitative ranges of real values of concentrations, for example, {Zero, Low, Medium, High, Very High, Highest}.

Conclusions

In a whole, the tools to support the investigation shall include:

- a model description of causal relationships between objects of interaction network;

- GMDH [6, 7] or neural network modules that approximate and qualitatively estimate direct functional relationships between objects of the model;
- a qualitative inference system that provides the investigator with qualitative reasoning about functional relationships of the model;
- a control system, which, under the investigator's request, filters out a required subset of mappings in the model, supplies neural network modules and qualitative inference system with required information, and supervises their operation.

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