根据植物茎叶图像模拟根系图像的人工神经网络算法

丛沛桐，祖元刚，于景华，赵则海，谷会岩
（东北林业大学森林植物生态学开放研究实验室，哈尔滨 150040）

摘要：以内蒙古野生甘草产区为试验地，采用图像关联的小波-神经网络综合算法建立了甘草茎叶-根系图像联结的 BP 人工神经网络模型。该模型具有运算速度快，易于处理复杂图像数据的特点。通过植物茎叶图像对根系图像的模拟，实现块茎植物生物量数量化评估和农作物估产。

关键词：植物根系；生物量评估；图像模拟；人工神经网络

Artificial Neuro-network to Simulate Root Systemimage by Botanic Leaf-stalkimage

CONG Pei-Tong, GU Lui-Yan, YU Jing-Hua, Zhao Ze-Hai, GU Lui-Yan (*Open research laboratory of Forest ecology of Northeast forest university* 150040, *China*). ***Acta Ecologica Sinica*, 2002, 22(2): 163～168.**

Abstract: The patterns of botanic root system exist in an obvious correlation with the organs over the ground, such as leaves, branches, and stalks. Different species present varied features which mirror biological habits of a species being in correlation with the pattern of its own structure. Related researches have shown that root number, weight, and diameter offer a close relationship with the corresponding parts over the ground, so that it is possible to simulate the root system image with the leaf-stalk image.

In accordance with the principle of phytoecology, and based on biological habits of licorice, this paper recommended the wild licorice population structure in Chifeng region of the Inner Mongolia as a sample to establish a model of licorice artificial neuro-network linking up the leaves and stalks to its root system by using the technique of artificial neuro-nework integrated with image-information computer treatment. Through learning, training, and self-adaptation with the neuor-network, the ability to recognize and simulate the root system of the neuro-network got to be improved successively. It could randomize a single or multiple licorice leaf-stalk images to simulate the correspoding root system image by applying of the artificial neuro-network technique. A goal of simulating botanic root system image from vegetable leaf-stalk image was achieved at long.

On-the-spot inivestigation at the wild licorice growing area in Chifeng region, Inner Mongolia, the author selected both of 4 sampling units and premesured sample spots, of which the data of thd former were employed for the simulation and training of the neuro-network, and the latter for the assessment of distinguishing the artificial neuro-network and its imitation capacity. Around hundred of licorice leaf-stalk images and related data were gathered at the sample plots, meanwhile, the bio-variables related to some environmental parameters of ecological geography were collected too.

The chosen geographic environmental factors involved 4 categories: soil type, moisture state in growing time period, slope direction, and the elevation, after the factors to be digitized, they were inputted into

基金项目：国家自然科学基金“九五”重大资助项目（39893360）；国家林业局专项调查资助项目
收稿日期：2000-09-20；**修订日期**：2001-08-27
作者简介：丛沛桐（1963～），男，黑龙江双鸭山人，博士，副教授。主要从事生态学研究。

the neuro-network model for computation. Digitized classification was grouped at 4 levels and the classified standards were determined to depend upon the concrete state of the trial sample plots.

The leaf-stalk and root system images of licorice are the major datum-source being employed for the artificial neuro-network model. The collection of patterns of the images were done standardizedly and formulatedly as well as possible. The photo-angle, height, and size were kept of showing no difference, and the color, light, and shade might be set strictlessly a little.

The simulated artifical neuro-network of licorice root system was designed to be a double-layer structure including each one of the input, hidden(mid-layer), and output layer. The transfer functions of the hidden and the output layer were the tansig and purelin type respectively. Thus, the output of data was realized in varied patterns. By auto-learning on counter propagation method and conducting the network to make a forward computation towards the sample input pattern, a comparison between the real output and the expected output of the network was made out, then adjusted the weighted average and the threshold value step by step until the faults got fulfilled to the requirement. To get pass of the above-mentioned understanding on the neuro-network and training well on the basis of weighted average, threshold value, and network structure, the simulation and prediction of a new sample can be approached successfully.

After getting the original image digitized, due to the data being very great and appearing of image noise, it couldn't be directly applied to learning and training for the neuro-network, for this reason, a wavelet image processing technique was recommended for the decomposition of licorice leaf-stalk image at 2～4 levels. The concrete way of doing was to divide the correlation leaf-stalk image into 4 groups, and each group was chosen of four typical images to represent the basical link-form types between licorice leaf-stalk over the ground and root system under the ground to mirror the variant ecological environment and seasonal conditions. The selected image data were colourful and typical, the original digitized image was 288 $\times$352 pixels, by two levels of wavelet image decomposition, the first level image-size was 151$\times$183 pixels, and the second, 83$\times$99 pixels, that were satisfied to fulfill the requirements of learning and training for the neuro-network. In the meantime, the corresponding high(H, V, D)and low(A)frequency images at each decomposed level were obtained. Of them, the high one was used for learning and training at the stage of establishing models, and the low one for synthesizing root system image at the stage of simulation.

The network input is the digital image of licorice leaf-stalk with appendant digital information of geographic environment, while the network output is the digital image and bio-variables of licorice root system. By learning and training with the inputted multiple correlative images of licorice root-stalk, the network possessed of a higher capacity to recognize the correlative characteristics of licorice root-leaf, in which the remaining energy was 90%, and the zero-number, all over 40%. The simulated images preserved most details and principal trace features of the original images, and the basic parameter values were proximate to the original images, so it could offer an efficient simulation and reestablishment about the morphological features of the root system. This denotes that the set-up artificial neuro-network possesses of a superior capacity to recognize and simulate the images, so it can be efficiently applied to the simulation study on licorice root-stalk images.

The created artificial neuro-network model was utilized with the datum-source of licorice static images, its data are easy to be gathered, but the simulated scope is limited, however, on the basis of improving the computing capacity of the neuro-network and enhancing the quality of hardwares, to collect datum-cource with video-frequency would be more available to the research for the simulation of a reginal botanical root system. By integrated neuro-network simulation technique with the treatment of remote-sensing image-data to set up an artificial neuro-network system of three correlative factors: remote-sensing image-overground stalk image-underground root system, being helpful to raise the differentiation rate and abilities to identify such the underground images as vegetable root system and mineral resources, and digi-

tized analysis capacity as well. In these fields, the artificial neuro-network would be expected to have widely appoication perspectives.

Key words: plant roots; evaluation of biomass; image simulate; neural networks (NN)
文章编号:1000-0933(2002)02-0163-06 **中图分类号**:Q948 **文献标识码**:A

地表浅层是大气圈、水圈、生物圈、岩石圈交界地带,生命活动十分活跃。植物根系广布于地表浅层,成为该地带主要的生命有机体,构成了生物圈的重要一环。植物的立地生长条件和物质能量循环通道有赖于根系的结构、形态和功能,研究植物根系具有重要意义。由于获取根系比较困难,目前在区域尺度上开展的植物根系研究工作较少,研究水平低,并进一步影响了植物地下根系生物量的计算和作物估产[1]。

植物根系形态与地上的枝、叶、茎等器官有明显的相关关系,其相关特征因物种而异,反映了物种的生物习性与自身结构形态间的关联,这种关联既反映了物种自身的个性,又反映了植物根系与茎叶相互关联的共性。相关研究证明:根数、根重和根直径分别与地上部分有显著相关状[2,3],使得由茎叶图像模拟根系图像成为可能。

依据植物生态学原理、人工神经网络技术和计算机图像信息处理技术[4],以内蒙古赤峰地区野生甘草为例,在基于甘草生物学习性的基础上,建立甘草茎叶与根系联结的人工神经网络模型。通过神经网络的学习、训练和自适应,逐步提高该网络识别和模拟根系图像的能力。对任意选取的 1 株或多株甘草茎叶图像,采用人工神经网络技术模拟出对应的根系图像,实现由植物茎叶图像模拟植物根系图像的目地。

1 数据采集

在内蒙古赤峰地区野生甘草产地进行了实地调查和数据采集,选择标准的试验样地和预测样地各 4 块,其中试验样地数据用于神经网络模拟和训练,预测样地数据用来评估人工神经网络的识别及仿真能力。在样地内采集和挖掘了甘草茎叶和根系对应图像及数据近百株,同时采集生物量等相关生态地理环境参数。

选择的地理环境因子有 4 类:土壤类型、生长期水分状况、坡向、海拔高度。对这些因子做数字化处理后,输入到神经网络模型中参与运算。数字化分级划分 4 个水平,分级标准根据试验地实际状况确定。

甘草茎叶与根系图像是人工神经网络模型采用的主要数据源,图像采集格式应尽量标准化和规范化。保持拍摄角度、高度和图像尺寸的一致性,色彩和明暗度条件可适当降低,

2 人工神经网络模型建立

人工神经网络模型是采用非线性传递函数建立的多层网络结构,网络层由大量简单元件(神经元、模拟电子元件、光学元件等)构成,网络层之间通过特有的连接方式组合成复杂的神经网络系统。人工神经网络具有并行分布的信息处理功能,用来模拟人脑的思维行为,通过"学习"或"训练"达到识别新样本(图像)的目的。人工神经网络最显著的特点是具有自学习能力,尤其当数据含有噪音、数值奇异或高度非线性时,通过建立各影响因素信息输入与信息输出之间的高度非线性映射关系,实现对复杂非线性问题的反演和预测。基于这些特点,人工神经网络在生态学的模式识别、复杂非线性生态学行为预测方面具有重要的应用前景。基于 BP(Backpropagation)神经网络算法具有较强的图像识别能力,本文也以其为基础构建网络模型。

对于单输出的 BP 神经网络,设任意节点 i 的输出为 o_{ik},并有 N 个样本$(x_k, y_k)(k=1,2,\cdots,N)$,对于任一网络输入 x_k,就会产生相应的网络输出 y_k,如果将节点 j 的输入表示为:

$$net_{jk} = \sum_i w_{ij} O_{ik} \tag{1}$$

其中,$O_{jk}=f(net_{jk})$,w 为权重,则推导出 BP 神经网络的算法如下:

$$\begin{cases} \delta_{jk} = f'(net_{jk}) \Sigma \delta_{mk} w_{mj} \\ \dfrac{\partial E_k}{\partial W_{ij}} = \delta_{jk} O_{ik} \end{cases} \tag{2}$$

为提高处理速度,本文采用了改进的 Fletcher-Reeves Update BP 网络修正算法[4,5]。

第一次搜索采用线性方式，便于快速计算初值和初始搜索路径：

$$w_{k+1} = w_k - \alpha_k g_k \tag{3}$$

w_{k+1}是修正的权重，w_k 是当前权重，g_k 是梯度，α_k 是学习速率，下同。

第二次搜索将修正原来的方向，新的搜索方向由式(4)确定：

$$p_k = - g_k + \beta_k p_{k-1} \tag{4}$$

根据 Fletcher-Reeves Update BP 修正算法，有：

$$\beta_k = \frac{g_k^T g_k}{g_{k-1}^T g_{k-1}} \tag{5}$$

当前的搜索总是与前次搜索路径相连且正交。

设计的甘草根系模拟人工神经网络是一个双层结构，包括一个输入层、一个隐层(中间层)和一个输出层(图 1)。隐层和输出层转换函数分别为 tansig 和 purelin 类型，从而实现了任意格式的数据输出。通过反向传播算法的自动学习，网络对样本输入模式作前向计算，然后比较网络的实际输出与期望输出，逐步调整权值、阈值，直至误差满足要求，通过上述神经网络的学习和训练过程，在训练好的权值、阈值和网络结构基础上可以实现对新样本的模拟与预测。

网络输入的是甘草茎叶数字化图像，并附加地理环境数字信息；网络输出是甘草根系数字化图像及生物量。

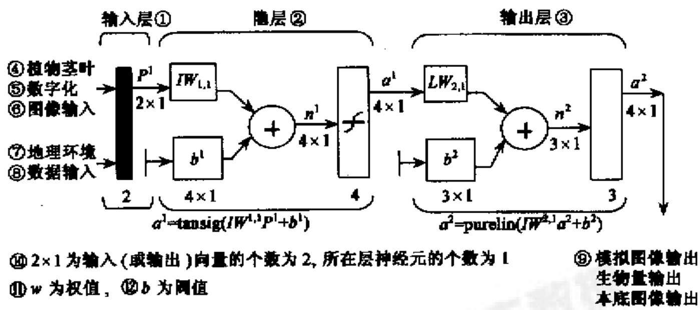

图 1 植物茎叶-植物根系双层神经网络结构图

Fig. 1 Structure of nueral network of plant ground culms - leafs and underground roots

① Input layer ② Hidden layer ③ Output layer ④ Plant leafs ⑤ Digitized ⑥ Image input ⑦ Geological environment ⑧ Data input ⑨ Simulated image, biomass, characteristical image ⑩ 2×1 2, number of vector 1, number of neurons ⑪ w, weight ⑫ b, threshould

3 图像数据处理

实地摄制的原始图像数字化以后是不能直接用于神经网络学习和训练的，主要是由于原始图像数字化形成的数值矩阵尺寸过大，导致神经网络训练精度低，图像识别能力下降。为此，采用小波图像处理技术对地面图像进行了 2～4 个水平的小波图像分解。首先将茎叶关联图像分为 4 组，用以代表不同的生态环境和不同季节甘草地面茎叶与地下根系联结，每一组又包括 4 幅图像，每幅图像都代表了甘草根系与地面茎叶之间基本的组合类型。具体图像小波变换技术如下方法实现。

对于一个离散输入信号 $f \in V_0$，多分辩分析算法如下：

$$f = \Sigma c_n^0 \phi_{0,n} = \Sigma c_n^1 \phi_{1,n} + \Sigma d_n^1 \psi_{1,n} \tag{6}$$

式中，ϕ 是多分辨分析中的尺度函数，ψ 是与 ϕ 有关的小波函数，其中：

$$\phi_{k,n} = 2^{-k/2}\phi(2^{-k}t - 2), \psi_{k,n} = 2^{-k/2}\psi(2^{-k}t - n) \tag{7}$$

式中，$\phi_{1,n}$与 $\psi_{1,n}$ 分别是字空间 V_1 和 W_1 的正交子空间，并且有：

$$V_0 = V_1, W_1 \tag{8}$$

沿 x 方向作一维小波变换后再沿 Y 方向作一维小波变换.两个方向上所作小波变换采用的小波母函数是相同的,必要时,还可以沿对角方向作小波变换,从而实现图像二维小波变换。

$$w_f(a_x,b_x,a_y,b_y)=\frac{1}{\sqrt{a_x a_y}}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\psi\left(\frac{x-b_x}{a_x}\right)\psi\left(\frac{x-b_y}{a_y}\right)f(x,y)\mathrm{d}x\mathrm{d}y \tag{9}$$

式中,ψ 是一维小波母函数。

原始数字化图像尺寸是 288×352,经过二维图像小波分解后,图像的尺寸得到了大幅度压缩。一级水平分解后的图像尺寸(数值矩阵)是 151×183,二级水平分解后图像尺寸(数值矩阵)是 83×99,已经可以满足神经网络学习和训练的要求。同时得到了对应各分解水平的高频图像(H,V,D)和低频图像(A),其中的高频图像用于建模阶段的网络学习与训练,低频本底图像用于根系图像模拟阶段的合成[6]。

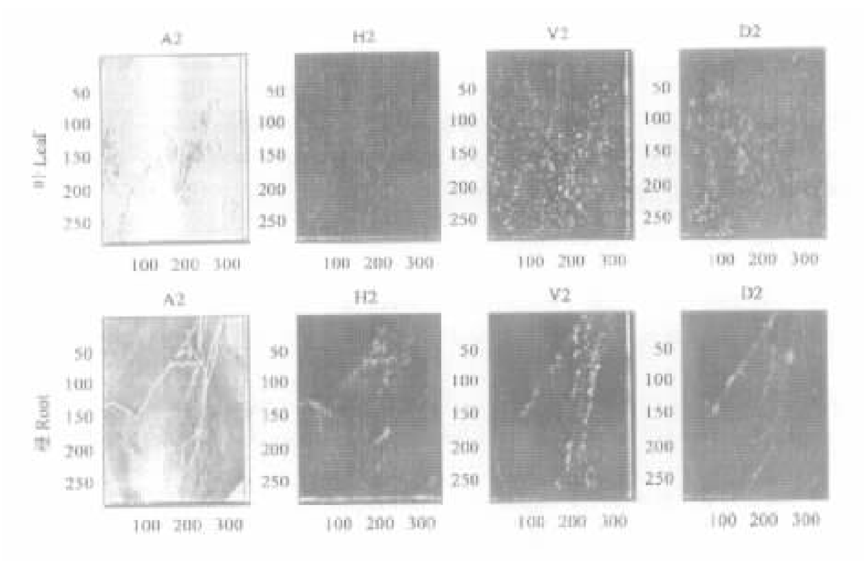

图 2　根叶联结二水平小波分解图像

Fig. 2　Decomposed images of 2 level wavelet of relation between roots and leaf

训练图像格式为彩色全真图像,本文在子波变换过程中,将其转换为灰度索引图像后,数值矩阵由原来的一个三维矩阵变换为 2 个二维色彩矩阵和图像矩阵,图像矩阵用于神经网络的模拟和运算,色彩矩阵用于图像色彩模拟与图像合成。

在神经网络模型中,输入多幅甘草根叶对应关联图像,通过对大量对应根叶关联的数字化图像进行学习训练,网络对甘草根叶关联特性具有了较高的识别能力。

3　模型验证及结果分析

在训练好的根茎特征联结人工神经网络上,加入验证图像来校合所建神经网络对实际甘草图像的模拟与识别能力。选取的验证图像尺寸和格式同于训练图像,甘草地面茎叶验证图像和地下根系验证图像同样进行了 2 个水平的二维图像小波变换,分解后的茎叶图像作为神经网络输入数据源,经网络计算后,得到根系高频数字图像矩阵,与根系低频图像合并后得到根系模拟图像(图 3)。

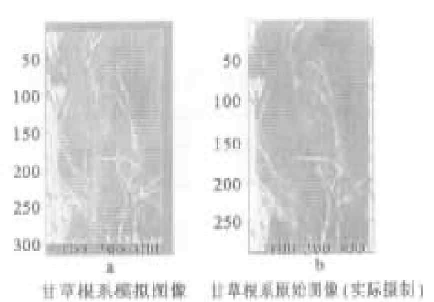

图 3　甘草模拟图像与原始图像对照图

Fig. 3　Contrast between reconstruct image and origin image

a. Liquorice rootsystem Simulated image,　b. Liquorice rootsystem Original image

经分析对比，模拟图像保留了原始图像的大部分细节及主要痕迹特征（分枝、延展），并且图像的基本参数特征都给予了明显的模拟和重建，表明所建人工神经网络具有较高的图像识别与模拟能力。

表 1 模拟图像和原始图像基本参数对照表

Table 1 Contrast between reconstruct image and origin image

图像编号 Number of images	剩余能量(%) Remain energy	零点数目(%) Zero number	一次分解阈值 Once decomposed shreshold	二次分解阈值 Twice decomposed shreshold
1#	99.96	41.16	3.5	3.5
2#	99.09	49.93	3	3
3#	99.87	42.5	3.5	3.5
4#	99.23	56.82	3.5	2.5

利用 BP 人工神经网络技术建立甘草茎叶图像与地下根系图像之间的联结，关键是图像数字化和小波分解等级的确定，根据已有的经验，在春秋季节，甘草图像噪声较小，2 个水平分解即可；在夏季，则以 3 个以上水平分解为宜。图像数字化尽可能采用双精度浮点格式，这种格式的数据可以直接用于神经网络运算，而不需要重复数据标准化处理工作。

本文所设计的人工神经网络是以静态图像为数据源进行图像模拟的，由于视频数据源具有快速捕捉地面茎叶图像的优点，在软硬件技术完备的情况下，模拟植物根系视频图像也是可行的。如果利用遥感图像数据，建立遥感图像-地面茎叶图像-地下根系图像 3 个关联要素的人工神经网络系统将有利于提高遥感图像的监测视野和对地下图像（包括植物根系、地下矿产）的识别与分析能力，在此方面，人工神经网络技术具有广阔的应用前景。

参考文献

[1] Zhang W H(张文辉),Zu Y G(祖元刚). Study on the individual growth dynamic of adenophora lobophylla——Growth dynamic in one growing season, *Bulletin of Botanical Research*(in Chinese)(植物研究),1998,**18**(1):119～127.

[2] Zhang W H(张文辉),Zu Y G(祖元刚). Study on the individual growth dynamic of adenophora lobophylla——The root system growth dynamic in the life span. *Bulletin of Botanical Research*(in Chinese)(植物研究),1998,**18**(1):128～135.

[3] Huang J H, *et al*. (黄建辉等). Study on bacteria population dynamics in cultural period and fish productivity in Tuerjishan Reservoir *Acta Ecologica Sinica*(in Chinese)(生态学报),1999,**19**(2):270～277.

[4] Zhang R H, *et al*. (张仁华等). Studing of CO_2 flux on surface phants by remote sensing. *Science in China*(*Series D*)(in Chinese)(中国科学 D 辑),2000,**30**(2):215～224.

[5] Jiang C X(蒋春曦). Distinguishing seismic wave and disturbing wave for local earthquake by BP neural net. *Seismological and Geomagnetic Observation and Research*(in Chinese)(地震地磁观测与研究)1998,**19**(5):64～67.

[6] Piao R M, *et al*. (朴荣民等). Application of the Theory of Two dimensional Wavelet Transformation to Kill Noise of the Seismic Signals. *Journal of Shenyang Institute of Chemical Technology*(in Chinese)(沈阳化工学院学报),1997,**11**(2):148～156.

[7] Hong W, *et al*(洪伟,等). A study on the model of forest resources management based on the artificial neural network, *Journal of Natural Resources*(in Chinese)(自然资源学报),1998,**13**(1):69～72.

[8] Zu Y G(祖元刚),Zao Z H(赵则海),Cong P T(丛沛桐),An elementary study on the distributional rule of canory gaps of *Larix gmelinii* forests using wavelet analysis. *Acta Ecological Sinica*(in Chinese)(生态学报),1999,**19**(6):927～931.

[9] Zu Y G(祖元刚),Zao Z H(赵则海),Cong P T(丛沛桐),Fractal analysis on spatial distribution patterns of population from *Quercus liaotunggensis* forest in Dangling Mountain, *Bulletin of Botanical Research*(in Chinese)(植物研究),2000:**20**(1):112～119.

[10] Michael E. Hasselmo. Simulating nerves and networks. *Science*,1999,**282**(5391):1055～1058.

[11] sellers P J. *et al*. Modeling the exchanges of energy, water and carbon between continents and the atmosphere. *Science*,1999,**275**(5299):502～506.