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Application of Bayesian networks in evaluation of current status and protection of *Pulsatilla patens* (L.) Mill.

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Citation: Sienkiewicz, A., and G., Łaska. 2021. Application of Bayesian networks in evaluation of current status and protection of *Pulsatilla patens* (L.) Mill. Ecosphere 12(1):e03337. 10.1002/ecs2.3337

Abstract. Understanding of the impact of environmental factors on endangered plant species provides a basis for assessment of the risk of their extinction in the near future. Of particular importance is the search for optimal environmental conditions to preserve the continued existence of endangered taxa. Thus, there is a need for a method based on mathematical modeling to connect the current status of an endangered plant species with changing environmental conditions. Using the basics of decision theory, we developed a mathematical model to assess the influence of changing habitat conditions on the current status and protection of *Pulsatilla patens* (L.) Mill., an endangered plant species in Europe, as an example. The mathematical model was based on the data from 43 sites in the 3 largest forest complexes in NE Poland from 2011 to 2014 (29 attributes, 1566 records). The graphical model showing significant cause-and-effect relations between morphological-developmental features of individuals, demographic features of the populations, and physicochemical properties of the soil was built using the Bayesian networks in GeNIe 2.0 (University of Pittsburgh, Pittsburgh, Pennsylvania, USA). In the process of modeling with the Bayesian Search Algorithm, we also performed simulation, prediction, and optimization of the effects of selected environmental factors on growth and development of the endangered taxon. The diagnostic testing and sensitivity analysis revealed that the degree of soil acidification is the major variable determining the size of populations (number of individuals), developmental phase (juvenile, vegetative, flowering), and size of the individuals (height and diameter of ground rosette). Using the approach presented in this work, it was possible to identify a new habitat factor not known to be important at multiple scales for growth, development, and population dynamics of *P. patens*. The validation showed that the developed model is the most effective for evaluation of the impact of habitat conditions on the population features important for reproduction of this taxon. Therefore, the model proposed is recommended as a tool to support decision-making aimed at conservation planning of the endangered plant species.

Key words: Bayesian networks; Bayesian Search Algorithm; cause-and-effect relationships; conservation planning; northeastern Poland; *Pulsatilla patens*; scheduled implementation; simulation and optimization.

Received 15 May 2019; revised 31 May 2020; accepted 23 July 2020; final version received 18 November 2020. Corresponding Editor: Julia A. Jones.

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INTRODUCTION

The protection of plant populations and biological diversity requires determination of the optimum environment conditions ensuring optimal development, growth, and reproduction of a given species (Łaska and Sienkiewicz 2014, 2015*a*). Determination of the ranges of abiotic and biotic environmental factors optimal for conservation of endangered species is an important

research task (Schulze et al. 2005, Hopkins and Hüner 2009). Identification of beneficial environmental conditions is a difficult process and must take into account disturbances caused by anthropogenic pressure, local population processes, and environmental fluctuations (Łaska 2001, Sienkiewicz 2012, 2014). An attractive solution would be a mathematical modeling procedure to describe the mutual relations and cause-and-effect dependencies between the development and population dynamics of an endangered plant taxon and environmental factors under disturbances. Here, we describe the use of a Bayesian network (BN) model for preservation of populations of endangered plant species. The model's network topology permits conclusions about the functioning of a given species in defined environmental conditions (Evans et al. 2008, Oleas et al. 2012). The model's graph structure also permits simulation, prediction, and optimization of environmental factors for the growth and development of the endangered taxon (Łaska and Sienkiewicz 2015*b*). Moreover, simulation of the occurrence of disturbances supports making accurate decisions regarding the functioning of a given species under variable environmental conditions (Pollino et al. 2007, Douglas and Newton 2014). The model also permits simulation of the impact of proposed protective measures on the functioning of the species (Ferson and Burgman 2006, Marcot 2006). Finally, the structure of the graphical model indicates the optimum range of variation of the environmental factors for further development of a given population. The proposed model can be supplemented with new information (new data from observations) and modified under conditions of high uncertainty (Drużdżel 2005). As BN models can be easily adapted to new situations, new elements that may be relevant for conservation of the population can be easily included (Uusatilo 2007). It is for these reasons that BN models have the potential to be valuable tools to support decision-making in plant conservation planning (Pollino and White 2005, Tantipisanuh et al. 2014).

To demonstrate application of decision theory for evaluation of the current status of an endangered plant species, we present a BN model (Pearl 1988) describing the effect of habitat features on the morphological-developmental and demographic features of *Pulsatilla patens* (L.) Mill. (Ranunculaceae) population in NE Poland. *P. patens* is a species of Boreo-meridional-continental distribution, and it is native to Europe, Russia, Mongolia, China, Canada, and USA. *P. patens* prefers areas that are used for cattle grazing on a regular basis, that is, along edges of forests and farmlands, and on stony hills (Uotila 1996, Kalliovirta et al. 2006). In the USA, the plants also grow in areas that are regularly used for grazing purposes, frequently burnt or mown, in pastures and prairies, along railway lines, and in cemeteries (Wildeman and Steeves 1982). In Germany, the plants prefer calcareous grasslands (Röder and Kiehl 2006); in Russia, steppe and wood-steppe communities (Rysina 1981); and in Estonia, different types of pine-dominated dry boreal forest (Pilt and Kukk 2002).

This species was chosen as it is endangered in Europe and included in the Enclosure II to the Habitat Directive (92/43/EWG) and Enclosure I of the Bern Convention. The European sub-species, *P. patens* ssp. *patens,* is found in central and middle-eastern Europe (Aichele and Schwegler 1957), with its northern limit of distribution at 66° northern latitude in Russia (Jalas and Suominen 1989). It reaches its western distribution limit in Sweden and Germany (Tutin and Akeroyd 1993), and the limit of permanent distribution in central Poland (Piękoś-Mirkowa and Mirek 2003). The best preserved and largest populations of *P. patens* ssp. *patens* are in NE Poland (Łaska and Sienkiewicz 2013). According to the results of monitoring, the number of sites of occurrence of this species and the number of individuals at particular sites have been continuously decreasing since 1955 (Juśkiewicz-Swaczyna 2010*a*, Monitoring GIOŚ 2010–2011). Preliminary analyses have suggested that conservation of this species depends mostly on habitat conditions (Łaska and Sienkiewicz 2013). Thus, application of effective measures ensuring conservation of the species first requires identification of its optimum habitat conditions.

Methods

Study area

We selected a study area in the NE Poland, where populations of *P. patens* occur in the three largest forest complexes belonging to Natura 2000 (www.

gdos.gov.pl), Knyszyńska Forest (Knyszyńska Refuge PLH200006 and Knyszyńska Forest PLB200003), Piska Forest (Piska Refuge PLH280048 and Piska Forest PLB280008), and Augustowska Forest (Augustowska Refuge PLH200005 and Augustowska Forest PLB200002; Fig. 1). As over 80% of sites of occurrence of this species are in the northeastern part of the country, the populations growing there were assumed to be representative, such that observations at those sites can support conclusions regarding the populations in the whole country. These sites reflect also the full range of environmental conditions in which the populations of this species occur. Table 1 presents the data characterizing the selected forests (area, climate, and vegetation cover).

Study species

P. patens (synonym *Anemone patens* L., Ranunculaceae) is a monoecious, long-lived perennial species (up to tens of years) with a vertically branching rhizome that can form several shoots, resulting in older plants forming clumps (Pilt and Kukk 2002). It is a hemicryptophyte and rhizophyte, which means that the centrifugal process of withering away of its woody underground organs may lead to the disintegration of the old individuals (Łukasiewicz 1962). The majority of researchers definitely deny the taxon's capacity for vegetative reproduction (Wójtowicz 2000, Kalliovirta et al. 2003). Within Poland, *P. patens* favors open locations with southwestern and southern exposure, typically on fringes of boreal forests (Matuszkiewicz 2001) or in slightly shady areas. It may also occur in ploughed sections of forests, forest glades, and fire-protection forest belts (Łaska and Sienkiewicz 2010).

This species is considered critically threatened in the flora of Czech Republic (Holub and Procházka 2000) and is included in the Red list and/or Red Data Books of Germany (endangered; Röder and Kiehl 2006), Sweden

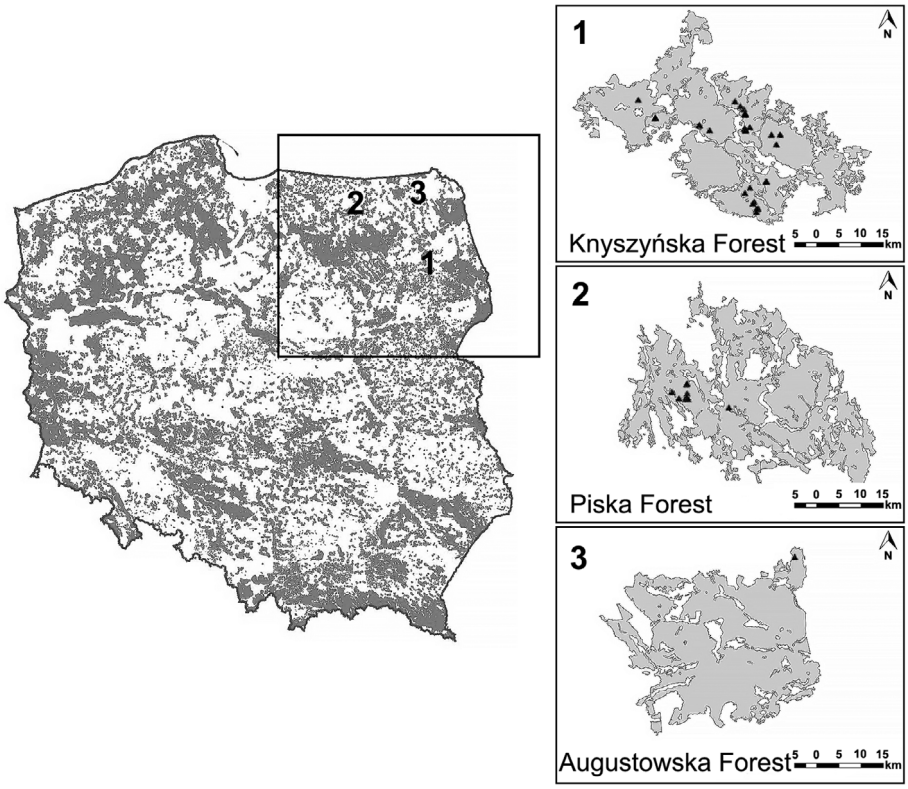


Fig. 1. Map of study area in Poland and location of *Pulsatilla patens* (L.) Mill. sites (www.bdl.lasy.gov.pl). Each site is described by the updated card of valuable plant species, (RDLP, Białystok).

Table 1. Characterization of the forestry study areas.

Criterion	Knyszyńska Forest	Piska Forest	Augustowska Forest
Area (km^2)	1267	1180	1144
Climate			
Year average air temperature (°C)	7	6.5–7.4	6.6
Average temperature in summer (°C)	18	17	16.7
Average temperature in winter (°C)	−3.5	−4.0	−4.8
Precipitations (mm)	550–650	565–631	372–761
Days under snow cover	85–90	75–92	90
Thickness of snow cover (cm)	10	10–15	10–15
Year average air humidity (%)	82	81–83	83
Duration of vegetation season (days)	200	200–205	190–195
Plant cover			
Dominant forest community	boreal	subboreal	boreal
No. forest associations	23	25	28
No. viscous plant species	835	900	1110
No. protected plant species	93	20	123

Note: Sources of climate data are Górniak (2000) (Knyszyńska Forest); RDLP, Olsztyn and Białystok (2013) (Piska Forest); and Sokołowski (2010) (Augustowska Forest).

(vulnerable; Gärdenfors 2000), Lithuania (relatively restored), Leningrad region of Russia (decreasing number), Latvia (data deficient; EUNIS 2005), Slovakia (Průša et al. 2005), and Kaliningrad District of Russian federation (Noskov 2000). In Finland and Estonia, the populations of *P. patens* are considered to be relicts (Pilt and Kukk 2002). This species has been classified to be protected within the programme Natura 2000 (Journal of Laws 2005, no. 94, item 795). In the Red List of Poland, it is classified as critically endangered (E category; Zarzycki and Szeląg 2006), and in the Red Data Book, it is listed as an endangered (EN) species (Kaźmierczakowa et al. 2014).

Population data

The current population status of *P. patens* was characterized at 43 sites (1566 individuals), including 33 sites in Knyszyńska Forest (843 individuals), 9 sites in Piska Forest (33 individuals), and 1 site in Augustowska Forest (690 individuals). The data were recorded in 2011–2014 in early spring when the greatest growth and development was observed. The population features recorded included type of distribution (such as random, aggregated) of individuals in a given population, size of population (number of individuals), structure of developmental phases (number of juvenile [J], vegetative [V], and flowering [F]), and size of individuals including height and diameter of the ground rosette and number of shoots. Cartographic distribution of *P. patens* individuals was determined using point-mapping and localization by GPS, which permitted determination of total size of population per unit area studied.

Soil parameters

Variation of habitat conditions at each of 43 sites studied was determined on the basis of laboratory analysis of representative samples of soil to the depth of 10–15 cm from the mixed mineral-organic layer from the place with the highest density of individuals. The soil samples were characterized by determination of the pH in 0.1M KCl (soil to potassium chloride ratio of 1:2.5; w/v as g/ml) using HQ40D meter (Hach, Loveland, Colorado, USA). Particle-size distribution was determined according to the hydrometer method (PN-R-04032:1998). The exchange acidity was determined by the Sokołov method, and hydrolytic acidity by the Kappen method with calcium acetate solution. Exchangeable bases were extracted with 1M ammonium acetate (Ostrowska et al. 1991), magnesium and calcium were measured by flame AAS (Avanta PM, GBC Scientific Equipment Pty, Braeside, Victoria, Australia), and Na and K were determined using flame photometer (BWB Technology, Newbury,

Berkshire, UK). Organic carbon in the soil was determined in TOC-L analyzer with SSM-5000A Solid Sample Combustion Unit (Shimadzu, Kyoto, Japan). After nitric acid/hydrogen peroxide microwave digestion in ETHOS One (Milestone s.r.l., Milan, Italy), the content of N was measured by the Kjeldahl method in Vapodest 50s analyzer (Gerhardt, Königswinter, Germany) and the content of P was determined by the ammonium metavanadate method (Ostrowska et al. 1991) using a UV-1800 spectrophotometer (Shimadzu, Kyoto, Japan). The contents of assimilable nutrients of Ca, Mg, K, Na, and P were measured by the AAS method.

On the basis of soil analysis, the total sorption capacity and degree of the soil saturation with bases were evaluated. The calculated C/N ratio was used as a measure of intensity of transformation processes of the organic component of soil.

Bayesian modeling of variables

The mathematical model was designed with the use of a database of 29 attributes and 1566 records as the initial data. The modeling was performed using Bayesian networks in the GeNIe 2.0 program (University of Pittsburgh, Pittsburgh, Pennsylvania, USA). Prior to preliminary modeling, the continuous-valued variables were subjected to discretization, based on expert opinion or using the literature as guidance. The number of states for each variable was less than five to achieve a compromise between model simplicity and accuracy. Our approach permitted design of a network of mutual relations among the nodes representing variables at the significance level $\alpha = 0.05$ using the Bayesian Search Algorithm:

$$P(A_i|B) = \frac{P(A_i)P(B|A_i)}{\sum_{j=1}^{\infty} P(A_j)\,P(B|A_j)}$$

where $P(A_i|B)$ is the conditional probability (a posteriori) of event A on condition that event B has occurred; $P(A_i)$ is the probability a priori of event A, $\sum_{j=1}^{\infty} P(A_j)\,P(B|A_j)$ is the sum of probabilities of event $A_1, A_2, \ldots, A_n$ (Drużdżel 2005).

The model structure of the directed acyclic graph (DAG) that contains prior probabilities of all nodes without predecessors and probabilities of all nodes with all possible combinations of their direct predecessors was obtained from the data, and then, the network parameters were determined. The probabilities that the model variables take values from certain ranges were presented in the form of conditional distribution of probability. Cause-and-effect relationships in the graph were defined based on the presence of edges that represent conditional dependencies between pairs of nodes. In order to draw conclusions on the obtained dependencies, the strengths of the dependencies were estimated and diagnostic testing was performed. The strength of each relationship between a child node and a parent node was quantified by a weight using the Euclidean distance function. Diagnostic testing was performed in order to establish the diagnostic value of the influence of habitat conditions on particular characteristics of the population. The results of testing helped identify the environmental factor that has the greatest influence on the population characteristics so the highest diagnostic value. Then, computer simulations of the impact of the habitat conditions on the status of *P. patens* population were made. The results of computer simulations permitted designing a mathematical model of performance of the threatened taxon across variable habitat conditions. At the next step, we optimized the modeled factors and established the ranges of environmental variables needed for adequate growth and development of *P. patens*. Bayesian Search Algorithm was also used for identification of disturbances in the functioning of the species caused by the lack of habitat conditions it prefers. In this way, we obtained information on the possible behavior of the taxon in response to modeling of the ranges of environmental variables.

Model validation.—The correctness of the mathematical model of the impact of habitat conditions on the status of *P. patens* population was verified on the test dataset using the method of tenfold cross-validation. In this method, 90% of the cases are used to train the model to find classifier parameters, and then, the model is validated by classifying the other 10%. This process is repeated ten times, each time using a different 90% of cases to create the parameters. In graphical presentation of the validation results, the confusion matrix describing the quality of validation for particular ranges of individual variables was taken into account.

Sensitivity analysis.—Sensitivity analysis was used to measure the degree to which a model

variable influences the target variable in the model, quantified through variance reduction. The higher the variance reduction value, the greater the influence on the target variable of the network. The sensitivity analysis permitted identification of important variables within the network and helped verify the behavior of the model.

Results

Current status of P. patens population

According to our observations, the largest size of *P. patens* populations, with the highest number of juvenile, vegetative, and flowering individuals, occurred in Knyszyńska Forest (Table 2). In the populations studied, the vegetative individuals were dominant. The greatest average height and average diameter of ground rosette were noted in the population growing in Augustowska Forest. The smallest average height and average diameter of ground rosette were noted in the population growing in Knyszyńska Forest. The greatest average number of shoots was observed in the population in Augustowska Forest, while the smallest average number of shoots was observed in Piska Forest.

Habitat conditions

In NE Poland, *P. patens* grows on sandy, mineral-humic soil. We studied 33 sites with Brunic Arenosols (typical rusty soil), 6 sites with Dystric Albic Brunic Arenosols (podzolic rusty soil), and 4 sites with Eutric/Epidystric Cambisols (leached brown soil) (Łaska 2006, data from Forest Divisions), of pH varying from strongly acidic to weakly acidic (Table 3). According to the Egner-Riehm limit levels, the soil samples

Table 2. Variability of population characteristics of *Pulsatilla patens* (L.) Mill. in NE Poland.

Characteristics of population	Knyszyńska Forest	Piska Forest	Augustowska Forest
Structure of developmental phases			
No. individuals	843	33	690
No. juvenile (J) individuals	42	...	...
No. vegetative (V) individuals	676	15	588
No. flowering (F) individuals	125	18	102
No. individuals in site ± $\bar{x}$SD	25.6 ± 81.3	3.7 ± 5.8	690
No. juvenile (J) individuals	1.3 ± 6.8	...	...
No. vegetative (V) individuals	20.5 ± 68.4	1.7 ± 3.9	588
No. flowering (F) individuals	3.8 ± 11.3	2.0 ± 1.9	102
Structure of size of individuals			
Height of individuals [cm] $\bar{x}$ ± SD	11.7 ± 7.6	18.7 ± 9.0	19.4 ± 7.9
Height of individuals in developmental phases [cm]			
Juvenile (J)	5.8 ± 1.7	...	...
Vegetative (V)	9.3 ± 3.5	11.2 ± 2.8	16.9 ± 3.7
Flowering (F)	26.3 ± 8.4	25.0 ± 7.4	33.9 ± 9.7
Diameter of rosette [cm] $\bar{x}$ ± SD	3.7 ± 3.7	3.8 ± 3.1	8.1 ± 5.6
Diameter of rosette of individuals in developmental phases [cm]			
Juvenile (J)	3.0 ± 3.4	...	...
Vegetative (V)	3.7 ± 3.8	3.6 ± 1.9	7.9 ± 5.5
Flowering (F)	4.1 ± 2.9	4.0 ± 3.9	9.0 ± 6.6
No. shoots			
No. shoots	4487	229	7242
No. juvenile (J) shoots	1043	72	48
No. vegetative (V) shoots	3244	127	7056
No. flowering (F) shoots	200	30	138
No. shoots per individuals ± $\bar{x}$SD	5.3 ± 4.9	6.9 ± 3.6	10.5 ± 6.9
No. juvenile (J) shoots	1.2 ± 2.0	2.2 ± 5.0	0.1 ± 0.3
No. vegetative (V) shoots	3.9 ± 7.7	3.9 ± 2.8	10.2 ± 8.5
No. flowering (F) shoots	0.2 ± 0.8	0.9 ± 1.4	0.2 ± 0.7

Note: ... "not noted".

Table 3. Physicochemical properties of soil at the sites of occurrence of *Pulsatilla patens* (L.) Mill. populations in NE Poland.

Properties of soil	Units	Knyszyńska Forest			Piska Forest			Augustowska Forest
		Min	Max	Mean	Min	Max	Mean	
Soil acidity								
pH	...	3.42	5.47	4.25	3.72	5.46	4.09	5.65
Granulometric composition								
Fraction 2.0	%	1	24	9.24	1	14	2.44	23
Fraction 1–0.1	%	63	93	78.27	73	89	84.61	66
Fraction 0.1–0.02	%	3	25	8.56	4	14	8.11	7
Fraction < 0.02	%	1	7	3.94	3	8	4.84	4
Sorption capacity								
Ca^{2+} (Ca-SC)	cmol(+)/kg	0.05	1.90	1.05	0.04	1.09	0.36	3.32
Mg^{2+} (Mg-SC)	cmol(+)/kg	0.03	0.95	0.35	0.01	0.08	0.03	0.19
K^{+} (K-SC)	cmol(+)/kg	0.02	0.25	0.15	0.02	0.06	0.02	0.04
Na^{+} (Na-SC)	cmol(+)/kg	0.01	0.08	0.04	0.01	0.02	0.01	0.02
Sum of cations (SC)	cmol(+)/kg	0.14	3.03	1.59	0.08	1.20	0.43	3.57
Hydrolytic acidity (HA)	cmol(+)/kg	3.83	18.34	6.68	1.69	8.18	5.68	2.29
Total sorption capacity (TSC)	cmol(+)/kg	4.03	21.37	8.27	2.89	8.70	6.10	5.86
Degree of saturation (DS)	%	1.81	32.03	18.33	1.28	41.52	8.82	60.92
Exchange acidity (EA)	cmol(+)/kg	0.06	2.07	0.74	0.03	1.60	1.21	0.13
Content of C, N, P, C/N								
Organic carbon (C)	%	0.77	9.41	2.27	1.46	3.74	2.28	1.90
Total nitrogen (N)	%	0.11	0.96	0.24	0.08	0.27	0.10	0.20
Total phosphorus (TP)	%	0.05	0.22	0.16	0.04	0.06	0.05	0.05
C/N ratio (C/N)	...	3.52	28.21	8.20	8.37	30.00	23.31	9.20
Nutrient concentrations								
P_2O_5 (P)	mg/kg	7.90	47.80	19.80	18.20	76.00	35.0	13.80
CaO (Ca)	mg/kg	0.30	666.90	34.30	0.10	667.80	66.10	3385.60
MgO (Mg)	mg/kg	0.40	160.10	15.20	0.70	28.20	9.50	220.10
K_2O (K)	mg/kg	0.90	67.30	23.20	10.70	29.50	21.20	26.30
Na_2O (Na)	mg/kg	0.70	10.90	7.20	1.30	5.80	3.20	8.40

Note: ... "not noted".

representing particular sites of *P. patens* populations were characterized by poor sorption capacity and low nutrient concentrations assimilable by plants.

BN population-habitat model

Analysis of the Bayesian network population-habitat model suggested that significant cause-and-effect relations occur among the degree of soil acidity; soil nutrient concentrations; soil granulometric composition; and the developmental phase of plants; number of flowering, vegetative and juvenile shoots; and diameter of ground rosette (Fig. 2). Degree of soil acidity and soil nutrient concentrations had the greatest effects on the population traits. Analysis of the conditional probability distribution determined using Bayesian Search Algorithm showed that *P. patens* preferred acidic soil of pH varying between 4 and 5 (the probability is 0.5). These pH values characterize mineral-humic soils, with predominance of sand whose content varies in the range 75–85% (probability is 0.4). The soil acidity limits the nutrient concentrations, which means that the content of CaO, MgO, and K_2O is below 50 mg/kg of soil and the content of Na_2O—below 10 mg/kg of soil (the probable content of K_2O and Na_2O is 0.9–1.0). The exception is the content of CaO which is above 150 mg/kg of soil and that of MgO above 100 mg/kg of soil at the site in Augustowska Forest, where the soil was of the lowest acidity (the probable content of CaO and MgO is 0.2–0.5). The content of P_2O_5 most often was below 20 mg/kg of soil (probability is 0.8). The content of organic carbon in the soil was below 2% (probability 0.5), and the C/N ratio was usually below 10 (probability 0.6; Fig. 3).

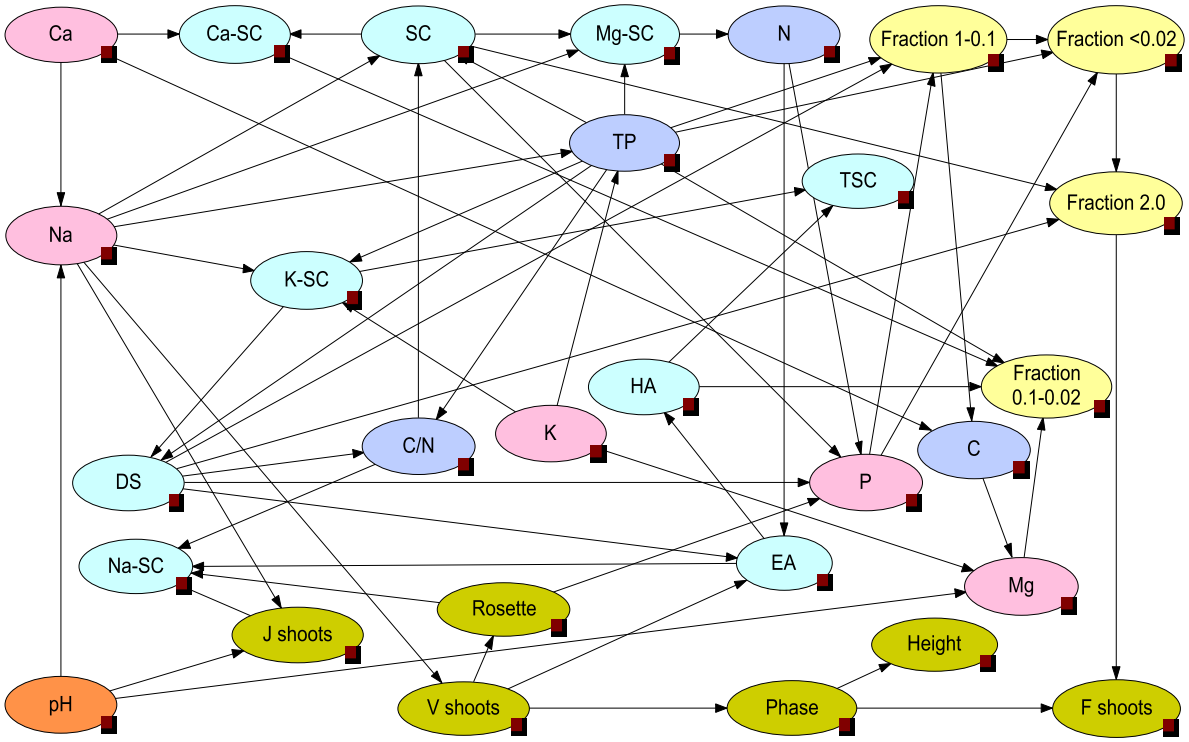


Fig. 2. BN model of the impact of habitat conditions on the characteristics of *Pulsatilla patens* (L.) Mill. populations (abbreviations of variable names were adopted according to the Table 3).

On the basis of morphological-developmental features, it was estimated that the populations studied were usually composed of vegetative individuals (probability 0.8). The modeled physicochemical properties of the soil at different sites of *P. patens* were not conducive to the presence of flowering and juvenile individuals. Moreover, at the assumed fertility of the upper layers of the soil, usually no juvenile and flowering individuals were observed (probability 0.2–0.3). The populations studied were composed of individuals of the height below 10 cm, showing from 1 to 5 juvenile shoots (probability 0.3; Fig. 3).

Model testing.—According to diagnostic testing, the presence of juvenile individuals and juvenile shoots depends mostly on the degree of the soil acidity (diagnostic value 0.06). Also, the presence of juvenile and flowering individuals and juvenile and flowering shoots depends on the degree of soil acidity (diagnostic value 0.04), which also affects the height of individuals and the diameter of their ground rosette (diagnostic value 0.02).

Model performance.—On the basis of cross-validation, it was established that the model proposed is the most effective for evaluation of the impact of habitat conditions on the presence of flowering shoots (accuracy value 0.84), developmental phase (accuracy value 0.82), and juvenile shoots (accuracy value 0.66). Prediction of the impact of habitat conditions on the other morphological-developmental traits is less accurate (accuracy value < 0.6; diameter of ground rosette 0.51, height 0.48, number of vegetative shoots 0.36).

Sensitivity analysis.—The analysis of the model sensitivity revealed that the degree of soil acidity has a strong influence on the size of population, developmental phase, and height of individuals, while the soil nutrient concentrations have a smaller influence (Fig. 4).

Model simulations

Results of the computer simulation indicate that with increasing pH of the soil (pH > 5), the nutrient concentrations in soil increases. At the content of CaO and MgO below 50 mg/kg of soil, K_2O below 25 mg/kg of soil and Na_2O below 10 mg/kg of soil, the population is composed mostly of vegetative individuals, while at CaO

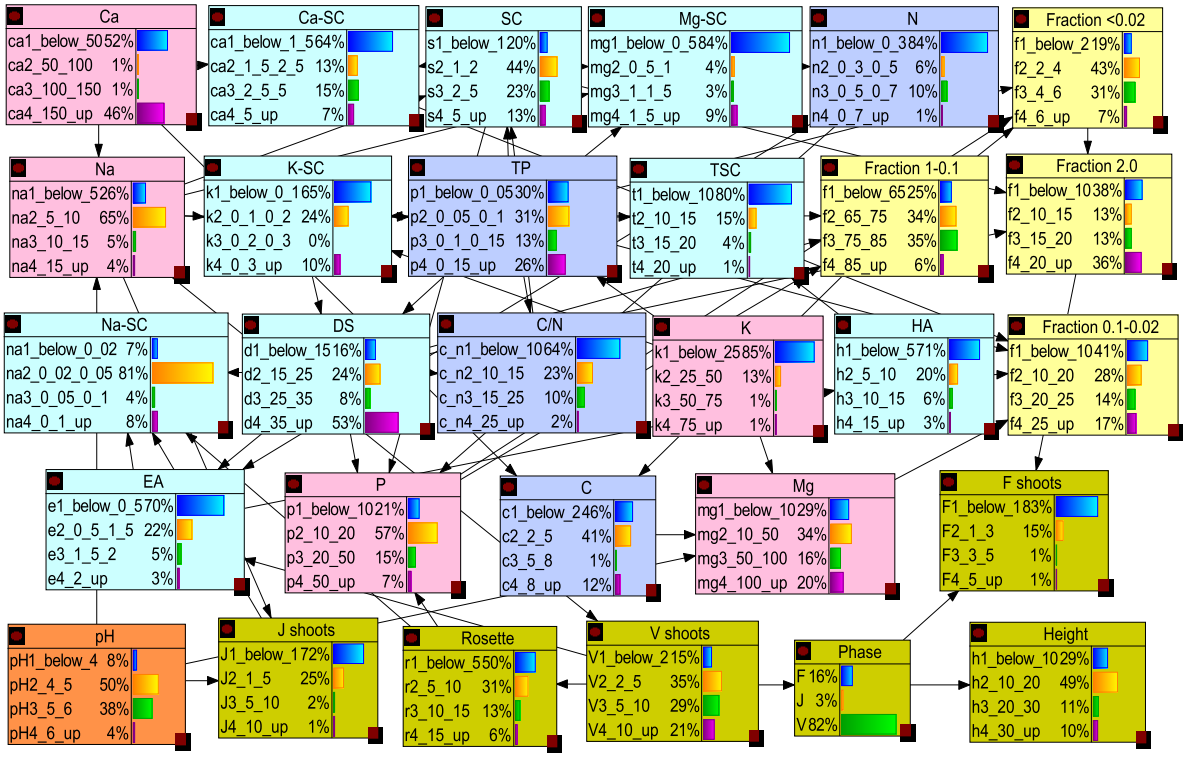


Fig. 3. Distribution of conditional probability of variables in BN model of the impact of habitat conditions on the characteristics of *Pulsatilla patens* (L.) Mill. populations.

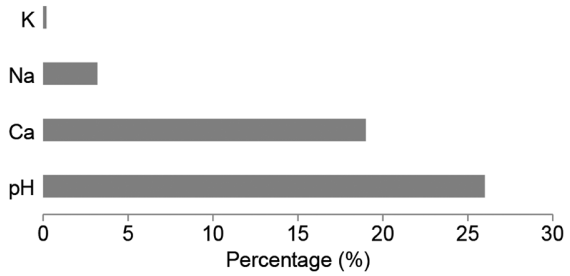


Fig. 4. Graphical presentation of the sensitivity analysis results of BN model, expressed as the percentage variance reduction of target variable of *Pulsatilla patens* (L.) Mill.

and MgO above 50 mg/kg of soil, K_2O above 25 mg/kg of soil and Na_2O above 10 mg/kg of soil, the contribution of flowering and juvenile individuals increases (probability of occurrence of these individuals in population is 0.3). Moreover, with increasing pH and fertility of the soil (nutrient concentrations), the contribution of flowering individuals taller than 10 cm increases, as does the number of flowering and vegetative shoots, and consequently the number of individuals of ground rosette diameter greater than 5 cm.

Discussion

Habitat-population modeling with the use of Bayesian networks is particularly useful for planning conservation of populations of endangered plant species. It is widely used in plant conservation biology (Marín et al. 2003), conservation management (Newton et al. 2007), and risk assessment (Pollino et al. 2007) because it permits determination of cause-and-effect relations between the developmental biology and dynamics of an endangered taxon and environmental factors (Łaska and Sienkiewicz 2014, 2015*a*). The use of this model is particularly helpful for determination of current status of populations of endangered species when only some ranges of

variation of environmental factors are known (Uusitalo 2007, Newton 2010, Chen and Pollino 2012). Moreover, the proposed network topology permits drawing probabilistic conclusions on responses of endangered species to habitat transformations caused by disturbances. The model also permits evaluation of the effectiveness of the intended protective measures (Wade 2000, Drechsler et al. 2003). Bayesian networks are also used in modeling the distribution of rare species (Aguilera et al. 2010), success of their relocation (Johnson et al. 2010), habitat impact on conservation (McNay et al. 2006), and monitoring in order to protect them (Wilson et al. 2008).

The goal of this study was to demonstrate the possibility of using Bayesian networks for evaluation of the current status of an endangered plant species. Although our study presents the application of the BN modeling approach to populations of *P. patens*, this approach can be applied to populations of other endangered species. Mathematical modeling with the use of the Bayesian Search Algorithm permitted designing of a universal model of population functioning in changing environmental conditions, which can support decision-making aimed at preservation of endangered plant species. The model permitted the identification of interrelationships and cause-and-effect relations that have impact on growth and development of a given species.

Besides the direct relationships among the modeled variables, we also determined the probability that the variables assume values from certain ranges. The structure of the Bayesian network obtained in the process of modeling also provided distribution of conditional probability of occurrence of morphological-developmental traits of individuals, demographic features of *P. patens* populations, and physicochemical properties of soils. Analysis of the model of interrelationships also provided the most probable configurations of variables, in light of the available observations. On this basis, it was possible to define the current status of *P. patens* populations and the habitat conditions in which this species occurs in NE Poland.

The results revealed that the traits of *P. patens* populations are mostly determined by the degree of soil acidity and the nutrient concentrations. On the basis of the distribution of conditional probability of the model variables, the populations of *P. patens* were found to prefer the soil of pH of 4–5, which agrees with the pH values determined as preferred by the species by Zarzycki et al. (2002). The soil of the highest acidity was found in the *P. patens* sites in Knyszyńska Forest (pH of 3.4), while the lowest acidity was measured at the site in Augustowska Forest (pH of 5.7). Lower acidity of soil has a significant effect on soil processes, including the more intensive development of microflora and higher rate of organic matter decomposition (Bednarek et al. 2011). These processes are conducive to faster release of ions and increase the nutrient concentrations available to plants. According to the pH values of the soil samples collected, the best soil conditions for growth and development of *P. patens* are in Augustowska Forest. This relation is confirmed by the fact that the individuals growing in Augustowska Forest are characterized by several times higher values of the morphological-developmental traits (height of individuals and diameter of rosette) than the plants from the other forest complexes studied. On the other hand, perhaps local populations of *P. patens* have adapted to specific environmental conditions and plant communities.

It seems that the factor modifying the variation of traits of *P. patens* in this forest complex may be the fertility of the upper soil level, enriched in charcoal left after forest fire. The soil samples collected from the sites of *P. patens* occurrence are characterized by small sorption capacity and low nutrient concentrations. Their pH in KCl ranges from 4.1 to 5.1, and the contents of available nitrogen, phosphorus, magnesium, and potassium are low (Wójtowicz 2000). The contents of CaO, MgO, and K_2O reach 50 mg/kg of soil and that of Na_2O is up to 10 mg/kg of soil. The greatest contribution of humus was found at the sites in Knyszyńska Forest. However, the content of humus was lower than that reported from the site of *P. patens* in Estonia (Pilt and Kukk 2002). The C/N ratio reaching 10 follows from the presence of acidic humus in the sites of NE Poland, showing a medium level of organic substances decomposition. According to the results of our model, the variation of traits of *P. patens* at the forests sites in NE Poland depends also on the nutrient concentrations in the soil. This relation is most pronounced at the site in Augustowska Forest, at which the soil was the richest in

nutrients and there the *P. patens* individuals were characterized by the highest values describing the morphological-developmental traits. Pilt and Kukk (2002) have found that in Estonia, at the sites of *P. patens*, where the soil was characterized by higher pH (pH in H_2O varied from 5.1 to 8.4), higher content of nitrogen (0.05–1.34%) and phosphorus (6–101 mg/kg of soil) and potassium (35–274 mg/kg of soil), there were 29 populations of this species composed of over 10,000 individuals. The presence of such a high number of individuals of this species in Estonia may also be related to the higher content of humus in the soil at this site (3.26–31.14%).

The results obtained from the model suggest that habitat conditions have an impact on the current status and condition of a rare plant species. It was found that in the optimum conditions (as seen in Augustowska Forest), the population has the highest number of individuals, the highest number of shoots per individual, and the highest number of individuals in the flowering phase. Kalliovirta et al. (2006) have also noted that at the sites of the optimum soil parameters and appropriate thickness of forest litter, the number of *P. patens* individuals was the highest. Thick litter covering the soil has a negative effect on blooming of *P. patens*. According to Schulze et al. (2005), a thick layer of forest litter may delay the heating of soil and hinder the development of buds. This observation has been confirmed by Röder and Kiehl (2006), who noted the statistically significant impact of the litter on the presence of juvenile individuals and blooming of adult individuals of *P. patens*. Moreover, according to Kalliovirta et al. (2006), the number of flowers in individuals of this species is negatively correlated with the thickness of forest litter at the site of the population.

The suitability of application of Bayesian networks to support decision-making (Uusitalo 2007) regarding conservation of endangered plant species was demonstrated by the results of simulations, prediction, and optimization of the impact of physicochemical properties of soil on the *P. patens* populations studied. Taking into account the graphical structure of the model, we determined the conditional relations among the variables considered (Newton 2010, Chen and Pollino 2012). Including description of the nodes after introduction of the assumed variation ranges of variables to the model, we obtained distributions of conditional probability a posteriori of particular variables (Newton 2010, Chen and Pollino 2012). Updating of the distributions of probabilities of variables in the process of simulation and prediction permitted identification of the optimum ranges of environmental parameters for conservation of a given population. Analysis of the distributions permitted estimation of potential losses following from the deviations of environmental conditions from the optimum ones for a given population.

As indicated by the results of computer simulations, with increasing pH and fertility of the soil, the population becomes dominated by tall and blooming individuals, and the number of shoots (including flowering and juvenile ones) in individuals increases. The optimum contents of meta ions are as follows: CaO and MgO from 50 mg/kg of soil, K_2O from 25 mg/kg of soil, and Na_2O from 10 mg/kg of soil. The effectiveness of flowering reproduction considerably depends on the conditions at sites where propagules are dispersed (Raven and Johnson 2002). As far as the individuals reproducing through seeds are concerned, of particular importance are the so-called safe sites of germination (Shivanna and Tandon 2014). Uotila (1969) has emphasized that in Finland *P. patens* prefers sites at which the layer of moss and litter is damaged. According to Juśkiewicz-Swaczyna (2010*b*), in the populations growing in the army training ground in Orzysz, *P. patens* individuals grow where the litter cover ranges from 5% to 30%, while in forests sites it grows where the mean litter cover averages $14.45 \pm 11.75\%$ (Juśkiewicz-Swaczyna and Choszcz 2012). A relation between the occurrence of *P. patens* and litter cover was also observed in the forests of NE Poland. No presence of *P. patens* individuals was noted where the litter cover was over 80%, while the most numerous populations were found where the litter cover was lower than 10% (62%). A smaller number of individuals were found where the litter cover was up to 30% (32%), while the lowest percentage (6%) were found where the litter cover ranged from 31 to 80%. It should be noted that at the high litter cover (50–80%) the presence of single individuals or individuals only in vegetative phase was observed, but the occurrence of populations of this species was not excluded. This

observation indicates that in the developmental cycle of *P. patens*, effective renewal of population requires a high diversity of habitats.

The BN model presented in this study is characterized not only by reliability, but also fulfils many criteria such as transparency and user convenience. The model contains a conditional probability distribution for every combination of variables and can thus provide any distribution instantly. Our approach can provide fast responses to queries once the model is compiled. Moreover, this approach can proceed not only from causes to consequences, but also deduce the probabilities of different causes given the consequences. The probabilistic presentation of the interactions in the presented model allows for the estimation of risks and uncertainties in plant conservation planning better than models that only account for expected values. The consequences of various management decisions can be also studied with regard to the risks of highly undesirable outcomes. Additionally, there are small sample sizes required to perform the modeling process and the presented analysis can exhibit good prediction accuracy even with rather small sample sizes (Uusitalo 2007). Unlike many standard statistical methods, the procedure can handle situations with missing observations, whether the data are missing randomly or the absence of an observation is dependent on the states of other variables. It is important that in addition to defining the model structure ourselves, it is also possible to use data to train the structure of BN model. The limitations of this model are mainly expert knowledge and the ranges of states of the environment present at the field sites. Therefore, analysis of the data using standard models would not allow obtaining similar conclusions about the impact of the degree of soil acidity or other environmental factors on the current status and condition of a given threatened plant species. Traditionally, the statistical modeling tools available for plant conservation planning are useful for identification of relationships. However, these relationships can be more difficult to determine because the plant habitat is changed by disturbances. Thus, cause-and-effect relationships between the biology of development and dynamics of plant taxa and the impact of environmental factors are better distinguished by mathematical modeling. Therefore, Bayesian modeling presented in this study can be a useful alternative approach to preservation of populations of endangered plant species.

In the near future, the authors plan to complete the presented model with biotic (biocenotic) interactions, which are difficult to account for but that could have more powerful influence on populations than abiotic variables.

Acknowledgments

We thank A. Drużdżel and M. Drużdżel for kind assistance in developing the data using GeNIe 2.0. We thank Dr Jason Hoeksema who gave help in the English translation and make a linguistic correction as a native speaker. This study was supported by a grant no. WZ/WB-IIS/2/2020 from the Ministry of Science and Higher Education of Poland.

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