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

Aneta Sienkiewicz and Grażyna Łaska

Department of Agri-Food Engineering and Environmental Management, Białystok University of Technology, Wiejska 45A, Białystok 15-351 Poland

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.

Copyright: © 2021 The Authors. This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

† E-mail: a.sienkiewicz@pb.edu.pl

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, 2015a). 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 2015b). 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, Tantipisanu 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 Boro-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 2010a, 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 hemicyryptophyte 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 Procházkova 2000) and is included in the Red list and/or Red Data Books of Germany (endangered; Röder and Kiehl 2006), Sweden...
(vulnerable; Gärdenfors 2000), Lithuania (relatively restored), Latvia (data deficient; EUNIS 2005), Slovakia ( Pruša 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 Szela 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 Sokolowski 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,

| Table 1. Characterization of the forestry study areas. | Knyszyńska Forest | Piska Forest | Augustowska Forest |
|-----------------------------------------------|-------------------|-------------|-------------------|
| Criterion                                    | 1267              | 1180        | 1144              |
| Area (km²)                                    |                   |             |                   |
| 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 Sokolowski (2010) (Augustowska Forest).*
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 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 $A_i$; $\sum_{j=1}^{\infty} P(A_j)P(B|A_j)$ is the sum of probabilities of event $A_1$, $A_2$, $\ldots$, $A_n$ (Druzdzel 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 \(\bar{x} \pm SD\) | 25.6 \(\pm 8.1\) | 3.7 \(\pm 5.8\) | 690                |
| No. juvenile (J) individuals| 1.3 \(\pm 6.8\)  | ...          | ...                |
| No. vegetative (V) individuals| 20.5             | 1.7 \(\pm 3.9\) | 588                |
| No. flowering (F) individuals| 3.8 \(\pm 11.3\) | 2.0 \(\pm 1.9\) | 102                |
| **Structure of size of individuals** |                   |              |                    |
| Height of individuals [cm] \(\bar{x} \pm SD\) | 11.7 \(\pm 7.6\) | 18.7 \(\pm 9.0\) | 19.4 \(\pm 7.9\) |
| Height of individuals in developmental phases [cm] | 5.8 \(\pm 1.7\) | ...          | ...                |
| Juvenile (J)               | 9.3 \(\pm 3.5\)  | 11.2 \(\pm 2.8\) | 16.9 \(\pm 3.7\) |
| Vegetative (V)             | 26.3 \(\pm 8.4\) | 25.0 \(\pm 7.4\) | 33.9 \(\pm 9.7\) |
| Flowering (F)              | 3.7 \(\pm 3.7\)  | 3.8 \(\pm 3.1\) | 8.1 \(\pm 5.6\)  |
| Diameter of rosette [cm] \(\bar{x} \pm SD\) | 3.0 \(\pm 3.4\) | ...          | ...                |
| Juvenile (J)               | 3.7 \(\pm 3.8\)  | 3.6 \(\pm 1.9\) | 7.9 \(\pm 5.5\)  |
| Vegetative (V)             | 4.1 \(\pm 2.9\)  | 4.0 \(\pm 3.9\) | 9.0 \(\pm 6.6\)  |
| Flowering (F)              | 5.3 \(\pm 4.9\)  | 6.9 \(\pm 3.6\) | 10.5 \(\pm 6.9\) |
| 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 \(\bar{x} \pm SD\) | 5.3 \(\pm 4.9\) | 6.9 \(\pm 3.6\) | 10.5 \(\pm 6.9\) |
| No. juvenile (J) shoots    | 1.2 \(\pm 2.0\)  | 2.2 \(\pm 5.0\) | 0.1 \(\pm 0.3\)  |
| No. vegetative (V) shoots  | 3.9 \(\pm 7.7\)  | 3.9 \(\pm 2.8\) | 10.2 \(\pm 8.5\) |
| No. flowering (F) shoots   | 0.2 \(\pm 0.8\)  | 0.9 \(\pm 1.4\) | 0.2 \(\pm 0.7\)  |

*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 K2O is below 50 mg/kg of soil and the content of Na2O—below 10 mg/kg of soil (the probable content of K2O and Na2O 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 P2O5 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).

**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 |
|-----------------------------------------------|-------|-------------------|--------------|-------------------|
| Soil acidity                                  |       | Min   | Max | Mean  | Min   | Max | Mean  | Min   | Max | Mean  |
| 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 1.0–1.1                               | %     | 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                              |       |       |     |       |       |     |       |       |     |       |
| Ca2+ (Ca-SC) cmol(+)/kg                        |       | 0.05  | 1.90 | 1.05  | 0.04  | 1.09 | 0.36  | 3.32  |     |       |
| Mg2+ (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                        |       |       |     |       |       |     |       |       |     |       |
| P2O5 (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|     |       |
| K2O (K) mg/kg                                  |       | 0.90  | 67.30 | 23.20 | 10.70 | 29.50 | 21.20 | 26.30 |     |       |
| Na2O (Na) mg/kg                                |       | 0.70  | 10.90| 7.20  | 1.30  | 5.80 | 3.20  | 8.40  |     |       |

Note: … “not noted”.

www.esajournals.org 7 January 2021  Volume 12(1)  Article e03337
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, K₂O below 25 mg/kg of soil and Na₂O below 10 mg/kg of soil, the population is composed mostly of vegetative individuals, while at CaO
K
Na
Ca
pH

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.

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 (Laska and Sieneńskiewicz 2014, 2015a). The use of this model is particularly helpful for determination of current status of populations of endangered species when only some ranges 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.
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 K2O reach 50 mg/kg of soil and that of Na2O 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 H₂O 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, K₂O from 25 mg/kg of soil, and Na₂O 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 (2010b), 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 ± 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 fulfills 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 relationships. However, these relationships are difficult to account for but that could have more powerful influence on populations than abiotic variables.

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.

**ACKNOWLEDGMENTS**

We thank A. Druzdzel and M. Druzdzel for kind assistance in developing the data using GeNle 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/2020 from the Ministry of Science and Higher Education of Poland.

**LITERATURE CITED**

Aguilera, P. A., A. Fernández, F. Reche, and R. Rumí. 2010. Hybrid Bayesian network classifiers: application to species distribution models. Environmental Modelling & Software 25:1630–1639.

Aichele, D., and H. W. Schwegler. 1957. Die Taxonomie der Gattung Pulsatilla. Feddes Repertorium 60:1–230.

Bednarek, R., H. Dziadowiec, U. Pokojska, and Z. Prusinkiewicz. 2011. Ecological and soil research. PWN, Warszawa, Poland.

Chen, S., and C. Pollino. 2012. Good practice in Bayesian network modelling. Environmental Modelling & Software 37:134–145.

Douglas, S. J., and A. C. Newton. 2014. Evaluation of Bayesian networks for modelling habitat suitability and management of a protected area. Journal for Nature Conservation 22:235–246.

Drechsler, M., K. Frank, I. Hanski, R. B. O’Hara, and C. Wissel. 2003. Ranking metapopulation extinction risk: from patterns in data to conservation management decisions. Ecological Applications 13:990–998.

Druzdzel, M. 2005. Intelligent Decision Support Systems Based on SMILE. Software Developer’s Journal 2:26–29.

Economic and Protective Forest Promotion Complex “Mazurskie Forests”. 2013. RDLP [Regional Directorate of National Forests]. Regional Directorate of National Forests. Olsztyn and Białystok, Poland.

EUNIS [European Nature Information System]. 2005. Species factsheet for Pulsatilla patens. http://eunis.eea.eu.int
European Communities. 2004. Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. Office for Official Publications of the European Communities, Luxembourg.

Evans, M. K., K. E. Holsinger, and E. S. Menges. 2008. Modeling the effect of fire on the demography of Dicerosfrutescens ssp. frutescens (Lamiaceae), an endangered plant endemic to Florida scrub. Population Ecology 50:53–62.

Ferson, S., and M. Burgman, editors. 2006. Quantitative methods for conservation biology. Springer-Verlag, New York, New York, USA.

Forest Data Bank. BULiGL [Forest Management and Geodesy], Raszyn, Poland. https://www.bdl.lasy.gov.pl

Gärdenfors, U. 2000. Population viability analysis in the classification of threatened species: problems and potentials. Ecological Bulletins 48:181–190.

Górniak, A. 2000. Climate of Podlaskie Province. IMGW Białystok Branch, Białystok, Poland.

Holub, J., and F. Procházk. 2000. Red List of vascular plants of the Czech Republic – 2000. Preslia 72:187–230.

Hopkins, W. G., and N. P. A. H.ardenfors. 2008. Evaluation of Western Ontario, Wiley & Sons, Hoboken, New Jersey, USA.

Jalas, J., and J. Suominen, editors. 1989. Atlas Florae Europaeae. Distribution of Vascular Plants in Europe 8. Nymphaeaceae to Ranunculaceae. Committee for Mapping the Flora of Europe, Societas Biologica Fennica, Vanamo, Helsinki, Finland.

Johnson, S., K. Mengersen, A. de Waal, K. Marnewick, D. Cilliers, A. M. Houser, and L. Boast. 2010. Modelling cheetah relocation success in southern Africa using an iterative Bayesian network development cycle. Ecological Modelling 221:641–651.

Journal of Laws. 2005. No. 94, item 795. Regulation of habitats and plant and animal species in need of protection in the form of determining the areas.

Juśkiewicz-Swaczyna, B. 2010a. Distribution and abundance of Pulsatilla patens populations in nature reserves in north-eastern Poland. Polish Journal of Natural Sciences 25:376–386.

Juśkiewicz-Swaczyna, B. 2010b. Population structure of Pulsatilla patens in relation to the habitat quality. Tuexenia 30:457–466.

Juśkiewicz-Swaczyna, B., and D. Choszcz. 2012. Effect of habitat quality on the structure of populations of Pulsatilla patens (L.) Mill. (Ranunculaceae) - rare and endangered species in European flora. Polish Journal of Ecology 60:565–574.

Kalliovirta, M., U. Kukk, and T. Rytäri. 2003. Pulsatilla patens (L.) Mill. In T. Rytäri, U. Kukk, T. Kull, A. Jäkäläniemi, and M. Reitalu, editors. Monitoring of threatened vascular plants in Estonia and Finland – methods and experiences. Finnish Environment 659:37–47.

Kalliovirta, M., T. Rytäri, and R. K. Heikkinen. 2006. Population structure of a threatened plant, Pulsatilla patens, in boreal forests: modelling relationships to overgrowth and site closure. Biodiversity and Conservation 15:3095–3108.

Każmierczakowa, R., K. Zarzycki, and Z. Mirek, editors. 2014. Polish red data book of plants. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków, Poland.

Łaska, G. 2001. The disturbance and vegetation dynamics: a review and an alternative framework. Plant Ecology 157:77–99.

Łaska, G. 2006. Dynamic tendencies of the secondary communities in the Knyszyńska Forest. Bogucki Publishing House, Białystok-Poznań, Poland.

Łaska, G., and A. Sienkiewicz. 2010. Eastern pasqueflower Pulsatilla patens (L.) Mill. in the Knyszyńska Forest. In Proceedings of the 55th meeting of the Polish Botanical Society, Acta Societatis Botanico-rum Poloniae 79:46, Polish Botanical Society, Warszawa, Poland.

Łaska, G., and A. Sienkiewicz. 2013. Condition and threat of the population of Pulsatilla patens (L.) Mill. under the influence of changing conditions of the natural environment in the Knyszyńska Forest. Pages 143–154 in I. Ciereszko and A. Baiguz, editors. Biodiversity - from cell to ecosystem. Plants and fungi in changing environmental conditions. Polish Botanical Society, Białystok, Poland.

Łaska, G., and A. Sienkiewicz. 2014. Mathematical modelling of the influence of air temperature on the conservation status and threat of Pulsatilla patens (L.) Mill. population in the Knyszyńska Forest. Episteme 22:173–179.

Łaska, G., and A. Sienkiewicz. 2015a. Mathematical modelling of relationships between the trophism of the upper layers of the soil and the characteristics of Pulsatilla patens (L.) Mill. population in the Knyszyńska Forest. Episteme 26:289–296.

Łaska, G., and A. Sienkiewicz. 2015b. Optimization of the impact of natural environment factors in terms of renewal of ecological environmental resources. Ecological Engineering 43:42–48.

Łukaszewicz, A. 1962. Morphologic development types of perennials. PTBN, Poznań, Poland.

Marcot, B. G. 2006. Habitat modeling for biodiversity conservation. Northwestern Naturalist 87:56–65.

Marín, J. M., R. M. Diez, and D. R. Insua. 2003. Bayesian methods in plant conservation biology. Biological and Conservation 113:379–387.
Matuszkiewicz, W. 2001. Guide for the determination of Polish plant communities. PWN, Warszawa, Poland.

McNay, R. S., B. G. Marcot, V. Brumovsky, and R. Ellis. 2006. A Bayesian approach to evaluating habitat for woodland caribou in north-central British Columbia. Canadian Journal of Forest Research 36:3117–3133.

Natura 2000. GDOŚ [General Directorate for Environmental Protection], Warszawa, Poland. www.gdos.gov.pl

Nature Inventory “Natura 2000”. 2007–2008. RDLP [Regional Directorate of National Forests], Białystok, Poland.

Newton, A. C. 2010. Use of Bayesian network for red listing under uncertainty. Environmental Modelling & Software 25:15–23.

Newton, A. C., G. B. Stewart, A. Díaz, D. Golicher, and A. S. Pullin. 2007. Bayesian belief networks as a tool for evidence-based conservation management. Journal for Nature Conservation 15:144–160.

Noskov, G. A. 2000. Red data book of nature of LEN. Springer-Verlag, New York, USA.

Oleas, N. H., A. W. Meerow, and J. Francisco-Ortega. 2012. Population dynamics of the endangered plant, Phaedranassa tungurague, from the tropical andean hotspot. Journal of Heredity 103:557–569.

Ostrowska, A., S. Gawliński, and Z. Szczubiałka. 1991. Methods of analysis and assessment of soil and plant properties. Institute of Environmental Protection, Warszawa, Poland.

Pearl, J. 1988. Probabilistic reasoning in intelligent systems. Morgan Kaufmann, San Mateo, Italy.

Perzanowska, J., editor. 2010. Monitoring of plant species. Methodological guide. Part I. GIOŚ [General Inspectorate for Environmental Protection], Warszawa, Poland.

Piękosi-Mirkowa, H., and Z. Mirek. 2003. Polish flora. Atlas of protected plants. MULTICO Publishing House, Warszawa, Poland.

Pilt, I., and U. Kukk. 2002. Pulsatilla patens and Pulsatilla pratensis (Ranunculaceae) in Estonia: distribution and ecology. Proceedings of the Estonian Academy of Sciences, Biology and Ecology 51:242–256.

Pollino, C. A., and A. K. White. 2005. Development and application of a Bayesian decision support tool to assist in the management of an endangered species in A. Zerger and R. M. Argent, editors. MODSIM 2005 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2005, Melbourne, Australia.

Pollino, C. A., A. K. White, and B. T. Hart. 2007. Examination of conflicts and improved strategies for the management of an endangered Eucalypt species using Bayesian network. Ecological Modelling 201:57–59.

Prusa, D., P. Eliáš, D. Dítě, L. Čačko, P. Krása, Z. Podešva, L. Kovář, M. Průšová, L. Hoshovec, and L. Adamec. 2005. Chráněné rastliny České a Slovenské republiky. Computer Press, Brno, Czechia.

Raven, P. H., and G. B. Johnson. 2002. Biology. Sixth. McGraw-Hill, Boston, Massachusetts, USA.

Röder, D., and K. Kiehl. 2006. Population structure and population dynamic of Pulsatilla patens (L.) Mill. in relation to vegetation characteristics. Flora 201:499–507.

Rysina, G. P. 1981. On the biology of Pulsatilla patens (L.) Mill. in the environs of Moscow. Bulletin of Moscow Society of Naturalists 86:129–134.

Schulze, E. D., E. Beck, and K. Müller-Hohenstein. 2005. Plant ecology. Springer-Verlag, New York, New York, USA.

Shivanna, K. R., and R. Tandon. 2014. Reproductive Ecology of Flowering Plants: a Manual. Springer-Verlag, New Delhi, India.

Sienkiewicz, A. 2012. Pulsatilla patens (L.) Mill. in the Krnzyńska Forest on background of abiotic disorders. Pages 103–116 in G. Laska, editor. Biodiversity - from cell to ecosystem. Polish Botanical Society, Białystok, Poland.

Sienkiewicz, A. 2014. The influence of abiotic factors on the structure of Pulsatilla patens (L.) Mill. in the Spychowo Forest District in the Piska Forest. Pages 251–260 in G. Laska, editor. Biodiversity - from cell to ecosystem. Threats to the environment and species protection of plants and fungi. Polish Botanical Society, Białystok, Poland.

Sokołowski, A. W. 2010. Augustowska forest. State Forest Information Center, Warszawa, Poland.

Tantipisanuh, N., G. A. Gale, and C. Pollino. 2014. Bayesian networks for habitat suitability modeling: a potential tool for conservation planning with scarce resources. Ecological Applications 24:1705–1718.

Tutin, T. G., J. R. Akeryo, et al. 1993. Pulsatilla Miller. Pages 264–266 in T. G. Tutin, editor. Flora Europaea - Volume 1: Psilotaceae to Platanaceae. Second edition. Cambridge University Press, Cambridge, UK.

Uotila, P. 1969. Ecology and area of Pulsatilla pratensis (L.) Mill. in Finland. Annales Botanici Fennici 6:105–111.

Uotila, P. 1996. Decline of Anemone patens (Ranunculaceae) in Finland. Acta Universitatis Upsaliensis Symbolae Botanicae Upsalienses 31:205–210.

Uusitalo, L. 2007. Advantages and challenges of Bayesian networks in environmental modelling. Ecological Modelling 203:312–318.

Wade, P. R. 2000. Bayesian Methods in Conservation Biology. Conservation Biology 14:1308–1316.
Wildeman, A. G., and T. A. Steeves. 1982. The morphology and growth cycle of *Anemone patens*. Canadian Journal of Botany 60:1126–1137.

Wilson, D. S., M. A. Stoddard, and K. J. Puetmann. 2008. Monitoring amphibian populations with incomplete survey information using a Bayesian probabilistic model. Ecological Modelling 214:210–218.

Wójtowicz, W. 2000. Biology, habitat requirements and perspectives of preservative cultivation of *Pulsatilla patens* (L.) Mill. Biuletyn Ogrodów Botanicznych 9:45–54.

Zarzycki, K., and Z. Szelał. 2006. Red list of vascular plants in Poland. Pages 9–20 in Z. Mirek, K. Zarzycki, W. Wojewoda, and Z. Szelał, editors. Red list of plants and fungi in Poland. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków, Poland.

Zarzycki, K., H. Trzcińska-Tacik, W. Różański, Z. Szelał, J. Wołek, and U. Korzeniak. 2002. Ecological indicator values of vascular plants of Poland. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków, Poland.