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ECOLOGICAL MANAGEMENT AND LEGAL FRAMEWORKS FOR FOREST BIO-RESOURCES IN EASTERN POLESIE: INTEGRATING *Vaccinium myrtillus* AND *Aronia melanocarpa* INTO EU BIODIVERSITY FRAMEWORKS AND INTERNATIONAL FOOD SAFETY STANDARDS

GESTÃO ECOLÓGICA E MARCOS LEGAIS PARA OS BIO-RECURSOS FLORESTAIS EM POLESIE ORIENTAL: INTEGRANDO Vaccinium myrtillus E Aronia melanocarpa NOS QUADROS DE BIODIVERSIDADE DA UE E NA POLÍTICA ALIMENTAR INTERNACIONAL NORMAS DE SEGURANÇA

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Oleksandr Lukash*
*T.H. Shevchenko National University "Chernihiv Colehium", Chernihiv, Ukraine
Orcid: https://orcid.org/0000-0003-2702-6430
lukash2011@ukr.net

Yevhenii Koshovets*
*T.H. Shevchenko National University "Chernihiv Colehium", Chernihiv, Ukraine
Orcid: https://orcid.org/0009-0001-1905-1874
y.koshovets@gmail.com

Oksana Sahach*
*T.H. Shevchenko National University "Chernihiv Colehium", Chernihiv, Ukraine
Orcid: https://orcid.org/0000-0002-4504-3405
oksmos78@ukr.net

Oleksandr Yakovenko*
*T.H. Shevchenko National University "Chernihiv Colehium", Chernihiv, Ukraine
Orcid: https://orcid.org/0000-0003-1417-6042
ajakov2@gmail.com

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Abstract

The sustainable management of forest bio-resources in the Eastern Polesie (Ukraine) requires a complex legal and ecological approach to meet global standards. This study evaluates the integration of native Vaccinium myrtillus L. and introduced Aronia melanocarpa (Michx.) Elliott into the EU biodiversity frameworks and international food safety protocols. Based on extensive field research in the Nevklia and Tupychiv forestries, we established that bilberry productivity in Molinio-Pinetum associations reaches 550 kg/ha, while intensive Aronia plantations yield up to 5,000 kg/ha. Ecotoxicological analysis verified that Lead (Pb) and Cadmium (Cd) concentrations in the fruits and shoots of both species (0.030–0.033 mg/kg dry weight) are 10–15 times lower than the Maximum Levels (MLs) established by the Codex Alimentarius (CXS 193-1995, 2025). Furthermore, the presence of rare orchids protected under the CITES Convention and the

Resumo

A gestão sustentável dos biorrecursos florestais na Polésia Oriental (Ucrânia) exige uma abordagem jurídica e ecológica complexa para atender aos padrões globais. Este estudo avalia a integração da espécie nativa Vaccinium myrtillus L. e da introduzida Aronia melanocarpa (Michx.) Elliott nos quadros de biodiversidade da UE e nos protocolos internacionais de segurança alimentar. Com base em extensas pesquisas de campo nos distritos florestais de Nevklia e Tupychiv, estabelecemos que a produtividade do mirtilo em associações de Molinio-Pinetum atinge 550 kg/ha, enquanto as plantações intensivas de A. melanocarpa rendem até 5.000 kg/ha. A análise ecotoxicológica verificou que as concentrações de Chumbo (Pb) e Cádmio (Cd) nos frutos e ramos de ambas as espécies (0,030–0,033 mg/kg de peso seco) são 10 a 15 vezes inferiores aos Níveis Máximos (MLs) estabelecidos pelo Codex Alimentarius (CXS 193-1995, 2025). Além disso, Red Data Book of Ukraine within managed forest areas confirms the ecological safety of this "dual-resource" model. The results provide a robust regulatory and methodological basis for the ecological management of forestry enterprises within the Emerald Network, ensuring compliance with the EU Biodiversity Strategy for 2030 and international GACP requirements.

Keywords: Ecological Management. Forest Bio-Resources. Codex Alimentarius. EU Biodiversity Strategy. Emerald Network.

a presença de orquídeas raras protegidas pela Convenção CITES e pelo Livro Vermelho da Ucrânia em áreas florestais manejadas confirma a segurança ecológica deste modelo de "recurso duplo". Os resultados fornecem uma base regulatória e metodológica robusta para a gestão ecológica de empresas florestais na Rede Emerald, garantindo a conformidade com a Estratégia de Biodiversidade da UE para 2030 e os requisitos internacionais de GACP.

Palavras-chave: *Gestão Ecológica. Biorrecursos Florestais. Codex Alimentarius. Estratégia de Biodiversidade da UE. Rede Emerald.*

1 INTRODUCTION

The Eastern Polesie represents a unique segment within the extensive belt of lowland sandy plains that stretch across Europe. These landscapes originated in crustal subsidence areas during tectonic depressions and underwent significant transformation during continental glaciations. As a periglacial zone. this region served as a vast accumulation basin for meltwater. which deposited substantial sandy material forming large lacustrine basins and outwash streams. Consequently. the Contemporary landscape is characterized by excessive moisture. extensive marshes. and wide floodplains. which differ significantly from the surrounding geographical regions (Lukash et al.. 2020).

On the weakly elevated sandy spaces. a specific ridge-and-hummock relief developed before the stabilization of the vegetation cover. Today. the Eastern Polesie is defined as a flat. waterlogged lowland plain where minerotrophic fens and bogged areas alternate with dry and moist pine forests on sands (Lukash et al.. 2020). These specific hydro-edaphic conditions–characterized by acidic. nutrient-poor sandy substrates and high water tables–provide the ideal ecological niche for acidophilic berry plants. particularly members of the *Ericaceae* and *Rosaceae* families.

The Nevklia and Tupychiv forestries. located within this geographic framework. serve as representative model sites for the Eastern Polesie (Branch "Horodnia Forest Enterprise" of the SE "Forests of Ukraine". 2024). These forest management units encompass the full spectrum of characteristic landscape elements–from hydromorphic depressions with gleyed soils to elevated sandy ridges. The high degree of preservation of natural forest structures. combined with the presence of active berry-producing areas. makes these forestries ideal polygons for evaluating the ecological management potential of both native and introduced bio-resources.

In the Eastern Polesie. *Vaccinium myrtillus* L. (bilberry) is not merely a berry crop but a dominant component of forest phytocenoses. acting as a crucial ecological indicator. It thrives in a narrow range of edaphic factors. preferring acidic (pH ~3.6). moist. and nitrogen-poor soils (Kislitsina. 2021. Timoshok. 2000). As a typical psychrophyte and oxylophyte. it defines the lower forest synpholia in pine and mixed forests where solar transmission is 15–35% (Ellenberg. 1974). Under its canopy. high-humus soils with increased cation exchange capacity and high buffering are formed. creating a stable microenvironment.

A cornerstone of its survival is the symbiotic relationship with ericoid mycorrhiza (ERM). This endophytic association. primarily with Ascomycota fungi. compensates for the plant's limited root system by mineralizing organic nitrogen into ammonium and facilitating phosphorus uptake via extracellular phosphatases (Read. 1973. Cai. 2021). This mycorrhizal network not only sustains the bilberry but also intensifies the natural regeneration of spruce and pine while preventing soil erosion.

Economically and medicinally. *V. myrtillus* is a recognized "superfruit." Its high concentration of anthocyanins (glycosides related to flavones) serves as a potent modulator of cellular pathways (Kalt. 2020. Tundis. 2020). Clinical data demonstrate that even moderate consumption–approximately 70g of berries or <50mg of anthocyanins per day–significantly reduces risks of cardiovascular disease. type 2 diabetes. and neurological decline (Cassidy. 2015. Jennings. 2014). Specific trials show that long-term intake (up to 170 days) leads to a significant decrease in inflammatory markers. such as C-reactive protein and IL-1β. and a reduction in "bad" cholesterol (LDL) while improving endothelial function (Zhu. 2013. Li et al.. 2015).

Furthermore. its role in ophthalmology is peerless. Anthocyanins selectively accumulate in ocular tissues. protecting the retina from oxidative stress by accelerating the regeneration of photosensitive pigments and improving capillary filtration (Bharat. 2018. Kalt. 2020). This is critical for preventing age-related macular degeneration and cataracts. Despite its resilience as a hemi-eurybiont in terms of climate. *V. myrtillus* remains a sensitive urbanophobe and gemi-stenobiont regarding soil conditions (Itsoil=0.45). making it highly vulnerable to anthropogenic factors like liming. biocides. or urbanization (Kislitsina. 2021).

Aronia melanocarpa (Michx.) Elliott. a species of North American origin. has established itself as a highly valuable crop in Europe due to its exceptional economic and medicinal properties. Genetic studies reveal that the genus *A. melanocarpa* maintains a complex balance between ploidy levels and speciation (Brand et al.. 2022). A critical factor for its widespread introduction is its reproductive strategy: while diploid individuals reproduce sexually. polyploids often exhibit apomixis. ensuring the stability of traits (Mahoney et al.. 2019). Crucially. unlike many introduced species. *A. melanocarpa* does not exhibit invasive behavior in European ecosystems. making it a safe candidate for large-scale agroforestry.

The phytochemical profile of the fruit is remarkably rich in polyphenols and anthocyanins. which can be further enhanced through specialized treatments (Duan et al.. 2023. Mezhenskyj et al.. 2024). These compounds underpin the plant's significant medicinal potential. particularly its cardioprotective and antioxidant effects (Buda et al.. 2021. Kokotkiewicz et al.. 2010). Beyond pharmacology. its economic utility is demonstrated in food technology. where chokeberry powder is used to create functional products like fortified bread (Petković et al.. 2021).

Modern biotechnological methods. including *in vitro* cultivation and successful acclimatization of cultivars like ‘Nero’. provide a robust basis for mass propagation (Ekiert et al.. 2021. Rusea et al.. 2022). Given its adaptability and high profitability (Gurčík et al.. 2023). *A. melanocarpa* is highly recommended for expanded cultivation. Specifically. the environmental conditions of the Eastern Polesie region in Ukraine offer an ideal habitat for integrating this "superfood" into local agricultural and forest ecosystems. ensuring both ecological safety and economic gain. Given its cardioprotective benefits (Buda et al.. 2021) and diverse applications in food technology (Petković et al.. 2021). expanding its cultivation in the suitable humid and acidic soils of Eastern Polesie is ecologically sound and economically profitable (Gurčík et al.. 2023).

Sustainable forestry management in Eastern Polesie requires a balanced approach to the utilization of both native and introduced berry resources. By aligning the management of the native *Vaccinium myrtillus* L. with the cultivation of the introduced

Aronia melanocarpa (Michx.) Elliott. forestry enterprises can optimize non-timber forest resources without compromising regional biodiversity. While *A. melanocarpa* shares similar ecological requirements with *V. myrtillus*. such as a preference for acidic. moist soils characteristic of the Polesie region (Mezhenskyj et al.. 2024). it importantly does not exhibit the invasive behavior of other North American woody species (Brand et al.. 2022). Its stable reproductive strategy–utilizing both sexual pathways and apomixis (Mahoney et al.. 2019)–ensures that it remains a predictable and manageable component of the forest understory.

The combined management of *V. myrtillus* and *A. melanocarpa* within the Eastern Polesie provides a sustainable model for agroforestry. By utilizing the vacant light-shade niches (where bilberry shows high tolerance. Itlight-shade = 0.89) and maintaining the mycorrhizal health of the forest floor. enterprises can increase biodiversity and economic resilience. This dual-resource strategy aligns with the European legislative framework on biodiversity by promoting native species conservation while safely integrating non-invasive. high-value introduced crops for functional food and pharmaceutical markets (Petković et al.. 2021).

Based on the necessity to align Ukrainian forestry practices with global standards. the aim of this study is to develop a scientifically grounded model for the ecological management of forest bio-resources in the Eastern Polesie. This involves a comprehensive evaluation of the resource potential. phytosociological stability. and ecotoxicological safety of native *Vaccinium myrtillus* L. and introduced *Aronia melanocarpa* (Michx.) Elliott. The study seeks to justify the "dual-resource" strategy as a tool for increasing the economic resilience of forestry enterprises while ensuring strict compliance with the EU Biodiversity Strategy for 2030. the Emerald Network requirements. and the Codex Alimentarius (CXS 193-1995) food safety protocols.

2 STUDY AREA. MATERIALS AND METHODS

2.1 Characteristics of the study area

The research was conducted within the specialized forest fund of the "Horodnia Forest Enterprise" branch (Chernihiv region. Ukraine). specifically focusing on two model sites: the Nevklia (6.026.0 ha) and Tupychiv (6.448.8 ha) forestries (Branch "Horodnia Forest Enterprise" of the SE "Forests of Ukraine". 2024). These areas represent the typical landscapes of the Eastern Polesie. situated within the Dnieper Lowland.

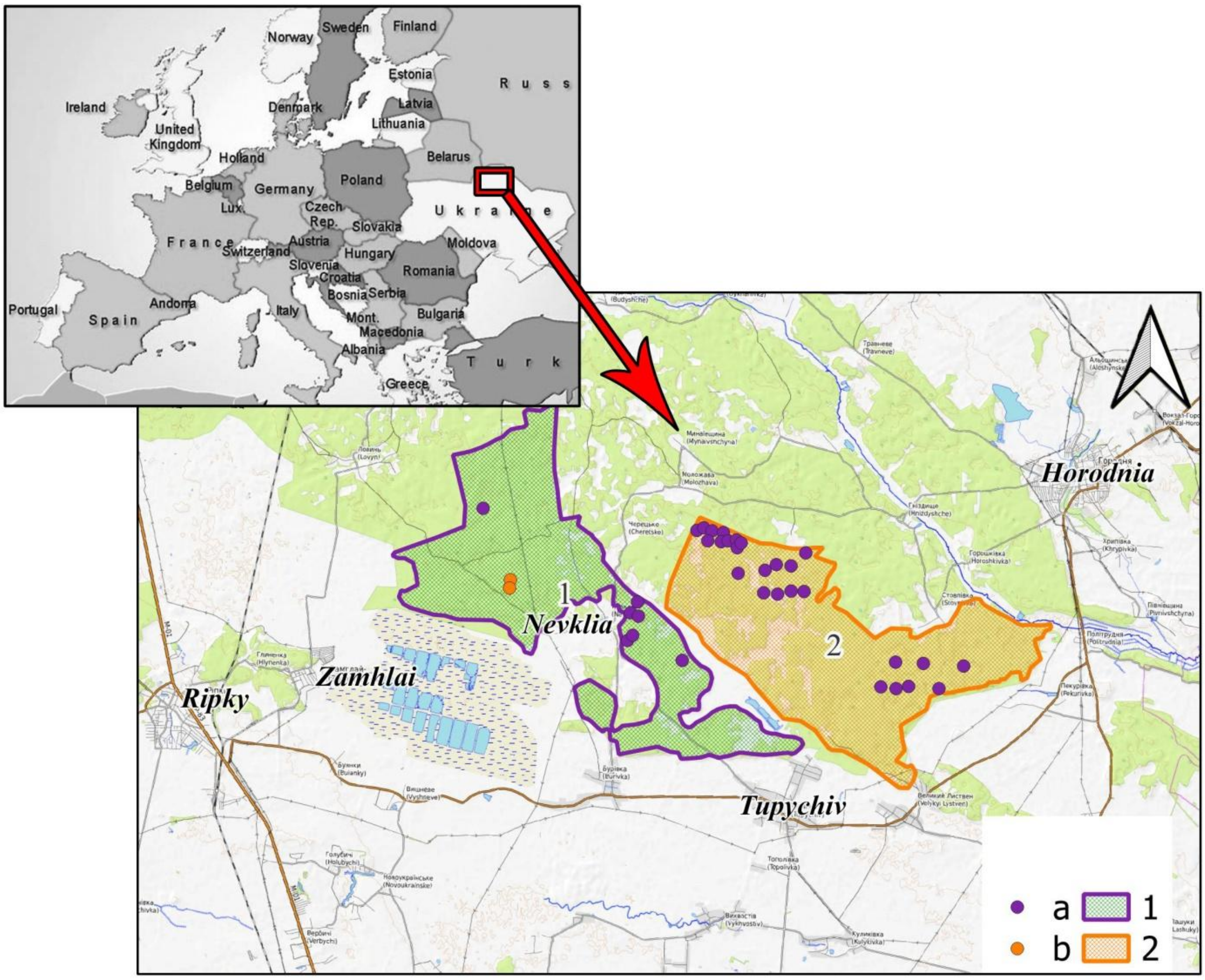
2.1.1 Physiogeographic and edaphic conditions

The relief of the study area is characterized as a flat-topped. slightly wavy sandy plain of moraine-glacial origin. with average altitudes reaching 150 m above sea level. The geological substrate consists of Paleogene and Cretaceous deposits covered by ancient alluvial and glaciofluvial sediments. Due to the high forest cover. erosion processes are minimally developed (State Forest Resources Agency of Ukraine. 2024a. b).

The soil cover is dominated by sod-podzolic soils (60%). primarily represented by sod-weakly and moderately podzolic types on sandy and sandy-loam rocks. In the Tupychiv forestry. the presence of sod-weakly podzolic deep-gleyed soils on ancient alluvium indicates a stable high moisture regime. which is an essential ecological factor for the sustainable development of both *Vaccinium myrtillus* and *Aronia melanocarpa* (Figure 1).

Figure 1

Natural berries of Vaccinium myrtillus(a) and Aronia melanocarpa plantations (b) in Nevklya (1) and Tupychiv (2) forestry



2.1.2 Climatic and hydrological framework

The climate is temperate-continental with an average annual temperature of +5.9°C and a growing season of 190 days. The average annual precipitation (570 mm) combined with the hydrothermal coefficient (HTC V–IX = 1.00–1.30) defines this region as a subzone of increased and good moisture. The hydrological network. belonging to the basins of the Dnieper. Sozh. and Snov rivers. is well-branched and provides a high degree of drainage. maintaining the hydro-edaphic balance necessary for acidophilic berry plants.

2.1.3 Forest typology and biodiversity conservation

According to geobotanical zoning. the territory belongs to the Horodnia district of oak-pine and pine forests. The forest stands are dominated by *Pinus sylvestris* L.. *Quercus robur* L.. and *Betula pendula* Roth. with crown closure ranging from 64% to 75%. These conditions create the specific semi-shaded light regime (15–35% solar transmission) required for the optimal functioning of the lower forest synpholia (State Forest Resources Agency of Ukraine. 2024a. b).

A significant portion of the model areas is integrated into the Emerald Network of Europe (European Environment Agency. n.d.): UA0000133 "Horodnianskyi" covers 4.741.2 ha in Nevklia and nearly the entire area (6.398.3 ha) in Tupychiv forestry. UA0000055 "Zamhlai" (506.3 ha) is also represented in the Nevklia forestry.

The ecological integrity of these sites is confirmed by the presence of rare species listed in the Red Data Book of Ukraine (Didukh. 2009). such as *Lycopodium annotinum* L. (a constant companion of bilberry). *Listera ovata* (L.) R.Br.. and *Lilium martagon* L. The strategic focus on natural regeneration (up to 7.0 ha annually) and the preservation of biodiversity-rich forest areas (over 1.000 ha combined) provides a scientifically grounded basis for the ecological management of both native (*Vaccinium myrtillus*) and introduced. non-invasive (*Aronia melanocarpa*) berry resources within the framework of European environmental safety standards.

2.2 Materials and methods

2.2.1 Geobotanical research

The field study of the vegetation was carried out by standard geobotanical methods (Yakubenko et al.. 2018). Vegetation relevés were taken during the biological optimum (May–August) on plots of 225–600 m². The experimental plots were chosen to be homogeneous in terms of ecological conditions and plant species composition. The participation of each species in the phytocenosis was assessed by the method of projective coverage.

2.2.2 Soil and plant sampling

The samples were collected in dry weather: *Vaccinium myrtillus* in July 2024 and *Aronia melanocarpa* in August 2025. Soil samples from each plot were collected by taking 5 subsamples (in 4 points at the corners of the plot and at 1 point in the plot center) using the “envelope” method (Kapanadze et al.. 2019). Sampling was performed at a depth of 15–20 cm. 200–250 g of each subsample was collected from 50 points in total. Plant sampling (leaves. stems. and fruits) was performed uniformly from all sides of the shrubs. Immediately after collection. samples were stored in clean paper bags and kept cool (Rautio et al.. 2020).

2.2.3 Laboratory analysis of heavy metals

All selected soil samples were dried in a drying stove at a temperature of 105°C for 24 h. Foreign impurities were removed by sifting through a 3 mm stainless steel sieve. According to the recommendations of Rautio et al. (2020). the leaves were thoroughly washed with distilled water before drying. then dried at 70°C. crushed. and homogenized using a special laboratory mill. Mineralization was carried out by dry ashing: samples were incinerated at 450–550°C for 24 hours (soil) and 48 hours (plants). The content of mobile forms of Cadmium (Cd) and Lead (Pb) was determined by atomic absorption spectrophotometry (SSU. 2025) using an atomic absorption spectrophotometer Spectr AA 240Z Varian AA DUO (Agilent Technologies. USA). A buffer solution of ammonium acetate (1 mol/l at pH 4.8) was used for extraction (soil:solution ratio 1:10. shaken for 2 hours).

2.2.4 Resource assessment and yield calculation

The yield of *V. myrtillus* was determined using the measuring method of S.M. Kozyakov (Myhal & Bokoch. 2017). Ten experimental plots of 1 m^2 were established for each phytocenosis type. Fruits were collected and weighed to determine the yield (*P*. kg/ha). The biological stock (*B*. kg) was calculated using the formula: $B = P \times S$. where

S is the area of the respective phytocenosis. For *A. melanocarpa*. yields were assessed based on three planting schemes (3×3 m. 3×1.5 m. 2×1.5 m) on 6-year-old plantations.

2.2.5 Regulatory and statistical analysis

The ecological management potential was evaluated through a comparative analysis of international and European legislative frameworks. including the Bern Convention (Council of Europe. 1979). the Nagoya Protocol (Secretariat of the Convention on Biological Diversity. 2011). and the EU Biodiversity Strategy for 2030 (European Commission. 2020). Compliance with global safety standards was verified against the Codex Alimentarius (Codex Alimentarius Commission. 2025) and WHO GACP guidelines (World Health Organization. 2003).

All statistical analyses were performed using STATISTICA 13.3 (TIBCO Inc.). Results are expressed as Mean +/- Standard Deviation (SD). with significance levels at $p < 0.05$. $p < 0.01$. $p < 0.001$.

3 RESULTS

3.1 International regulatory framework for biodiversity conservation and bio-resource safety in forestry

The ecological management of forest resources in the Eastern Polesie. specifically regarding *Vaccinium myrtillus* and *Aronia melanocarpa*. operates at the intersection of several global and European strategic frameworks. Compliance with these protocols is not elective but serves as a mandatory prerequisite for the integration of Ukrainian forestry products into the global market.

Biodiversity and habitat protection. The Emerald Network The cornerstone of conservation in the studied forestries is the Bern Convention (Council of Europe. 1979). The inclusion of the Nevklia and Tupychiv forestries in the Emerald Network (UA0000133 "Horodnianskyi" and UA0000055 "Zamhlai") imposes strict requirements for maintaining the "favorable conservation status" of habitats. Our identification of rare species such as *Platanthera bifolia*. *Epipactis helleborine*. and

Lycopodium annotinum necessitates a management model that prevents habitat fragmentation. This aligns with the EU Biodiversity Strategy for 2030 (European Commission. 2020). which emphasizes the protection of primary and old-growth forests as essential carbon sinks and biodiversity reservoirs.

Access and sustainable use. In accordance with the Nagoya Protocol (Secretariat of the Convention on Biological Diversity. 2011). the utilization of *V. myrtillus* and *A. melanocarpa* must be based on sustainable harvesting principles and equitable benefit-sharing. This framework justifies the transition from wild harvesting to semi-cultivated forest plantations (as seen in the Nevklia forestry). which reduces the pressure on natural populations while ensuring a stable supply of high-quality raw materials.

Food and pharmaceutical safety standards. The transition of Ukrainian forest products into the functional food and pharmaceutical sectors is governed by the Codex Alimentarius (Codex Alimentarius Commission. 2025). This joint FAO/WHO standard (CXS 193-1995) defines the maximum levels (MLs) for heavy metals like Lead (Pb) and Cadmium (Cd). Furthermore. for the medicinal use of bilberry shoots. the WHO Guidelines on GACP (World Health Organization. 2003) provide the methodological basis for ensuring that toxicological parameters are monitored from the soil to the final extract.

In this context. the ecological management of *V. myrtillus* and *A. melanocarpa* in the Eastern Polesie requires a multi-vector verification based on the aforementioned international protocols. Firstly. comprehensive phytosociological data are essential to fulfill the requirements of the Bern Convention. ensuring that resource exploitation does not compromise the "favorable conservation status" of Emerald Network habitats. Secondly. precise resource assessment data serve as the basis for the sustainable use principles outlined in the Nagoya Protocol. preventing the overexploitation of natural populations. Finally. the ecotoxicological analysis of soil and plant tissues acts as a direct verification of compliance with Codex Alimentarius (CXS 193-1995) and WHO GACP standards. Such a synchronized data set transforms traditional forestry into a robust ecological management system. guaranteeing that the production of certified. high-value bio-resources from the Eastern Polesie meets the safety and sustainability criteria of the global pharmaceutical and functional food markets.

3.2 Comparative analysis of berry resources in model forestries

The comparative assessment of the two model forestries reveals distinct resource strategies for both native and introduced species (Table 1).

Table 1

Comparative characteristics of berry resources in Nevklia and Tupychiv forestries

Parameter	Nevklia Forestry	Tupychiv Forestry
V. myrtillus – number of plots	7	~51
V. myrtillus – total area	~27 ha	~317 ha
Projective cover	30–40%	5–20%
Spatial distribution	Uniform / Non-uniform	Uniform-regular (universal)
A. melanocarpa area	0.6 ha (Comp. 51)	Not identified
Optimal forest types (TLC)	B3 DS. C3 DS	B2 DS. B3 DS
Most valuable plot	Comp. 87/10 (Reserve. 40%)	Comp. 14/1 (53 ha)

A fundamental difference was established in the structure of the *Vaccinium myrtillus* populations. In the Nevklia Forestry. bilberry demonstrates a higher density (projective cover of 30–40%). but its distribution is localized within a relatively small total area. This high density is primarily maintained due to the protective status of the local botanical reserve (Compartment 87).

In contrast. the Tupychiv Forestry represents a massive. continuous resource base exceeding 317 hectares. Although the average cover is lower (10–20%). the uniform-regular distribution across large compartments (such as the 53-hectare plot in Comp. 14) makes this forestry significantly more suitable for organized industrial harvesting.

The introduced *Aronia melanocarpa* is currently localized exclusively in the Nevklia Forestry. The successful 10-year exploitation of these plantations confirms the ecological safety and economic feasibility of the species. suggesting an urgent need for expanding plantation areas into suitable TLC (B3 DS. C3 GD) within both forestries to enhance the regional pharmaceutical and food resource base.

3.3 Phytocenological structure and taxonomic diversity of *Vaccinium myrtillus* communities

The syntaxonomic analysis of forest communities in the Eastern Polesie reveals a clear differentiation of *Vaccinium myrtillus* habitats depending on the moisture gradient and soil fertility. The studied phytocenoses are integrated into the classes *Vaccinio-Piceetea* Br.-Bl. 1939 and *Quercetea robori-petraeae* Br.-Bl. et Tx. ex Oberd. 1957. forming a stable ecological framework for berry resource management. Constancy classes (frequency) of differential and constant species of forest associations with Vaccinium myrtillus dominance are presented in Table 2.

3.3.1 Syntaxonomic hierarchy and dominance structure

The core of the natural bilberry resources is concentrated within the alliance *Dicrano-Pinion sylvestris* (Libbert 1933). The research identified three primary associations that define the resource potential of the region .

Molinio-Pinetum W.Matuszkiewicz et J.Matuszkiewicz 1973. Occupies the largest areas in humid depressions. These communities demonstrate a projective cover of *V. myrtillus* between 30–40%. The presence of moisture-loving diagnostic species. such as *Molinia caerulea* (L.) Moench and *Polytrichum commune* Hedw.. confirms a stable hydrological regime.

Peucedano-Pinetum W.Matuszkiewicz (1962) 1973. Represents fresher. well-drained habitats on sandy loam soils. The bilberry cover here remains stable at 30–40%. coexisting with *Convallaria majalis* L. and *Polygonatum odoratum* (Mill.) Druce.

Querco robori-Pinetum Matuszkiewicz 1981. These acidophilic pine-oak forests represent the highest degree of competitive vigor for *V. myrtillus*. where its dominance reaches 60%.

Table 2

Differential and constant species of forest associations with Vaccinium myrtillus dominance

Diagnostic and Constant Species	*Cladonio-Pinetum*	*Peucedano-Pinetum*	*Molinio-Pinetum*	*Querco robori-Pinetum*
Diagnostic group of associations				
Cladina rangiferina	V	-	-	-
Peucedanum oreoselinum	-	IV	-	-
Molinia caerulea	-	-	V	-
Carex sylvatica	-	-	-	IV
Constant species (Dicrano-Pinion / Vaccinio-Piceetea)				
Pinus sylvestris (I layer)	V	V	V	V
Vaccinium myrtillus (III layer)	III	IV	V	V
Pleurozium schreberi (IV layer)	III	V	IV	+
Dicranum polysetum	IV	IV	IV	II
Melampyrum pratense	III	V	V	V
Trientalis europaea	II	V	V	V
Species of Oak-Pine subors				
Quercus robur	-	II	II	V
Convallaria majalis	-	IV	I	V
Frangula alnus	-	I	IV	V

Notes. Roman numerals (I–V) indicate constancy classes (frequency).

3.3.2 Vertical organization and floristic composition

The forest stands of these communities. characterized by a canopy closure of 0.6–0.7. are formed by *Pinus sylvestris* L. and *Quercus robur* L. of I–II quality classes (bonitet). This density provides the optimal light transmission (semi-shade) required for the maximum productivity of the lower forest synpholia. The shrub layer is typically sparse (0.1–0.3). featuring species such as *Corylus avellana* L.. *Carpinus betulus* L.. and *Frangula alnus* Mill. This vertical "openness" of the understory allows for the formation of a dense herbaceous-shrub layer (total cover 40–50%). where *V. myrtillus* acts as a powerful edificator. The accompanying flora. including *Calamagrostis arundinacea* (L.) Roth. *Maianthemum bifolium* (L.) F.W.Schmidt. and *Melica nutans* L.. maintains a low projective cover (<1–5%). further emphasizing the monodominance of the bilberry.

3.3.3 Ecological stability and resource potential

The presence of rare and diagnostic species. such as *Lycopodium annotinum* L. and *Platanthera chlorantha* (Cust.) Rchb.. within these syntaxa underscores their high conservation value within the Emerald Network. The high ecological closure of these communities. evidenced by the minimal presence of ruderal or invasive species. provides a secure environment for the integrated management of native berries and the potential introduction of *Aronia melanocarpa* into similar ecological niches.

3.4 Phytocenological characteristics of *Aronia melanocarpa* forest plantations

The analysis of the structural and floristic organization of *Aronia melanocarpa* plantations within the study area reveals a unique ecological phenomenon: the successful integration of an introduced species into a stable forest environment without the degradation of native biodiversity. Despite the high density of the shrub layer (70–90%). these areas maintain a multi-layered structure and high species richness. characteristic of the forest-steppe and mixed forest zones.

3.4.1 Structural organization and coexistence

The primary layer is dominated by *A. melanocarpa*. which reaches its maximum vitality in these conditions. However. the data from the experimental plots demonstrate that the plantation does not form a biological "monoculture." Instead. it acts as a protective canopy for a diverse range of forest species. In several plots (Table 3. Nos. 4. 5. 6). a clear seasonal dynamics of the herbaceous layer was observed. with projective cover reaching 25% in the summer period.

The presence of natural tree regeneration within the plantation. including *Fraxinus excelsior* L.. *Acer platanoides* L.. and *Quercus robur* L.. indicates that the *Aronia* stands do not inhibit the natural successional processes of the native forest. Moreover. the presence of accompanying shrubs such as *Frangula alnus* Mill.. *Corylus avellana* L.. and *Viburnum opulus* L. suggests that *A. melanocarpa* occupies a specific niche in the understory that is functionally similar to native *Rosaceae* species.

Table 3

Structural and floristic parameters of forest plantations of Aronia melanocarpa

Ecological groups and parameters	Plot Nos. 1–3	Plot Nos. 4–6
Vegetation layer coverage (%)		
Shrub layer (A. melanocarpa)	70–85%	75–90%
Herbaceous layer (seasonal peak)	2–5%	15–25%
Moss layer	10–20%	0–3%
Native woody species (regeneration)		
Fraxinus excelsior. Acer platanoides	-	III
Quercus robur. Betula pendula	II	III
Diagnostic floristic elements		
Boreal (e.g.. *Pleurozium schreberi. Pyrola rotundifolia*)	V	II
Nemoral (e.g.. *Asarum europaeum. Aegopodium podagraria*)	III	V
Red Data Book species presence		
Platanthera bifolia	-	Present
Epipactis helleborine	-	Present
Lilium martagon	-	Present

Note. Roman numerals (II–V) indicate the presence/constancy of forest species under the Aronia melanocarpa canopy.

3.4.2 Floristic diversity and syntaxonomic links

The floristic composition under the *Aronia* canopy is a heterogeneous mixture of several ecological groups: nemoral elements (order *Fagetalia sylvaticae*) – species such as *Asarum europaeum* L.. *Aegopodium podagraria* L.. and *Galium odoratum* (L.) Scop. indicate high soil fertility and stable moisture levels. boreal elements (class *Vaccinio-Piceetea*) – the preservation of *Melampyrum pratense* L. and the moss *Pleurozium schreberi* (Willd. ex Brid.) Mitt. confirms the maintenance of the primary forest microclimate.

3.4.3 Conservation significance and rare species

The most significant finding of this study is the high frequency of rare and protected species within the *Aronia* plantations. Specifically. the presence of Red Data Book of Ukraine (Didukh. 2009) species. such as *Platanthera bifolia* (L.) Rich.. *Epipactis helleborine* (L.) Crantz. and *Lilium martagon* L.. proves that these managed forest areas serve as effective refugia for valuable biodiversity. The occurrence of *P. bifolia* in half of the studied plots. alongside *L. martagon*. demonstrates that the agricultural practices associated with *Aronia* cultivation (controlled thinning and localized maintenance) may even favor the stabilization of these rare populations by preventing overgrowth of more aggressive competitors.

In conclusion. *A. melanocarpa* plantations in the Eastern Polesie represent a sustainable model of agroforestry where economic utility and ecological conservation are balanced. The high degree of floristic saturation and the presence of rare orchids provide substantial evidence of the ecological safety and long-term viability of this species within the regional forest management framework.

3.5 Yield capacity and biological stock of *Vaccinium myrtillus* across syntaxonomic units

The productivity of *Vaccinium myrtillus* L. in the Eastern Polesie is significantly determined by the syntaxonomic affiliation of the forest communities. which reflects the complex influence of hydro-edaphic conditions and light regimes. The assessment of 30 experimental plots revealed a clear gradient in berry yield across the identified associations (Table 3).

Table 3

Biological yield and stock of V. myrtillus fruits in the studied forest associations

Association	Total area (ha)	Average yield (kg/ha)	Total biological stock (kg)
Molinio-Pinetum	2.24	550.0	676.5
Peucedano-Pinetum	1.44	412.0	534.3
Querco robori-Pinetum	1.14	242.5	276.3

3.5.1 Analysis of high-productivity habitats (Molinio-Pinetum)

The highest biological yield was recorded within the *Molinio-Pinetum* association (550 kg/ha). as shown in Figure 2a. These communities. situated in humid depressions on gleyed soils. represent the ecological optimum for bilberry fruiting. Individual plots showed the most stable outputs. contributing to a total biological stock of 676.5 kg. The high water table and specific microclimate of these "wet" pine forests ensure maximum berry weight and density.

Figure 2

Comparison of yield between wild common bilberry and cultivated black chokeberry from equal areas (50 m²): a – fruits of Vaccinium myrtillus harvested within the the most productive forest phytocenoses of – the Molinio-Pinetum association (weight: 2.5 kg). b – fruits of Aronia melanocarpa harvested from a plantation with a standard planting scheme of 3×3 m (weight: 11.5 kg)

3.5.2 Productivity of fresh pine and oak-pine forests

The *Peucedano-Pinetum* association demonstrates moderate productivity with an average yield of 412 kg/ha. Despite a lower projective cover compared to the previous group. these sites maintain a significant resource potential due to stable soil moisture. The lowest yield capacity was observed in the *Querco robori-Pinetum* association (242.5 kg/ha). which is more than twice lower than in *Molinio-Pinetum*. This reduction is attributed to the increased competitive pressure from the dense shrub layer (*Frangula alnus*. *Corylus avellana*) and the shading effect of the complex multi-layered canopy of pine-oak subors.

The total biological stock of bilberries across the 4.82 ha of intensively studied plots amounted to 1.487.1 kg. The findings confirm that while the largest areas of distribution may occur in drier subors. the primary commercial and ecological value is concentrated in the moist. acidophilic communities of the *Vaccinio-Piceetea* class.

3.6 Productivity and technological optimization of *Aronia melanocarpa* plantations

The assessment of the economic potential of *Aronia melanocarpa* in the Nevklia Forestry reveals a clear dependence between the planting scheme. yield capacity. and the physiological stability of the stands. The use of high-density planting models (intensive schemes) not only optimizes the forest area but also significantly accelerates the onset of commercial fruiting.

3.6.1 Influence of planting schemes on yield and phytocenotic stability

Research on the 6-year-old plantations (linked to the floristic descriptions in the phytocenological tables) established that the intensity of resource output correlates directly with the density of the shrub layer.

Standard scheme (3×3 m) represented by plots Nos. 2 and 4 (shrub cover 70–75%). The average yield by the third year reached 2.5 t/ha (25 c/ha) (Fig. 2b).

Moderately dense scheme (3×1.5 m) corresponds to plot No. 1 (shrub cover 80%). The yield increased to 3.5 t/ha (35 c/ha).

Intensive high-density scheme (2×1.5 m) recorded in plots Nos. 3. 5. and 6 (shrub cover 85–90%). This model showed the maximum productivity of 5.0 t/ha (50 c/ha).

The high projective cover (80–90%) in dense plantings acts as a natural biological filter. effectively suppressing the expansion of heliophilic weed species (ruderal flora). which is confirmed by the minimal presence of such species in the floristic tables.

3.6.2 Physiological adaptation and winter hardiness

Technological compaction of the stands induces a specific physiological response in *A. melanocarpa*. In dense rows. shoot growth ceases significantly earlier in the season compared to sparse plantings. This ensures superior wood maturation and shifts the metabolic focus toward the accumulation of nutrients in flower buds and the preparation for dormancy.

Furthermore. the dense structure of these forest plantations facilitates enhanced snow accumulation during the winter period. providing an additional thermal buffer against low temperatures. These factors combined contribute to the high winter hardiness and stable annual fruiting of *Aronia* within the Eastern Polesie. even under fluctuating climatic conditions.

3.7 Ecotoxicological assessment of berry resources

An essential aspect of evaluating the potential for industrial utilization of *Vaccinium myrtillus* and *Aronia melanocarpa* in the Eastern Polesie is the determination of heavy metal accumulation levels. particularly lead (Pb) and cadmium (Cd). The analysis of 40 samples (5 per point) revealed that the studied areas maintain high ecological purity. well within the safety standards of the European legislative framework.

Table 4

Concentration of heavy metals in soil and plant organs of Aronia melanocarpa and Vaccinium myrtillus (mg/kg dry weight. Mean ± SD)

Plant / Metal	Soil	Branches	Leaves	Fruits
Aronia melanocarpa				
Lead (Pb)	0.193 ± 0.141	0.055 ± 0.049	0.023 ± 0.026*	0.030 ± 0.047
Cadmium (Cd)	0.145 ± 0.033	0.080 ± 0.023	0.043 ± 0.013	**0.065 ± 0.026** ***
Vaccinium myrtillus				
Lead (Pb)	0.135 ± 0.177	0.025 ± 0.044	**0.128 ± 0.151** **	0.033 ± 0.046
Cadmium (Cd)	0.168 ± 0.131	0.038 ± 0.028	0.065 ± 0.047	0.008 ± 0.009

Note. Significance levels relative to the accumulation between species: * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

In all studied points. the concentration of Pb and Cd in fruits remained significantly below the maximum permissible levels (MPL) for berries. The average Pb concentration in fruits was virtually identical for both species (0.030–0.033 mg/kg). indicating the equal suitability of native and introduced species for the functional food industry.

Vaccinium myrtillus exhibited a significantly higher capacity for Pb accumulation in leaves compared to *Aronia* (0.128 vs 0.023 mg/kg. $p < 0.01$). Conversely. *Aronia melanocarpa* showed a higher selective accumulation of Cd in its fruits (0.065 mg/kg) compared to the exceptionally low levels in bilberries ($p < 0.001$).

The low transfer coefficients from soil to branches and fruits confirm the effective physiological barrier of both plants against toxic elements in the Polesie forest ecosystems.

4 DISCUSSION

4.1 Eco-cenotic optimum and interspecific synergy in forest communities

The comparative analysis of the ecological niches of *Vaccinium myrtillus* and *Aronia melanocarpa* in the Eastern Polesie reveals a high degree of eco-physiological compatibility. which serves as a biological foundation for integrated forest management. According to the indicator scales of Ellenberg (1974). both species exhibit pronounced acidophilic and hemi-sciophilous (semi-shade tolerant) properties. which is confirmed by our findings in the Nevklia and Tupychiv forestries.

The phytosociological research established that the maximum resource potential of *V. myrtillus* (up to 550 kg/ha) is realized within the *Molinio-Pinetum* association (class *Vaccinio-Piceetea*). These habitats. characterized by high soil moisture and gleying (Kislitsina et al.. 2021. Timoshok. 2000). align with the ecological requirements of *A. melanocarpa*. Although *Aronia* is an introduced species of North American origin. its physiological adaptation in the study area demonstrates that it successfully occupies a niche functionally similar to native understory shrubs like *Frangula alnus* and *Sorbus aucuparia* (Ekiert et al.. 2021). Our floristic tables show that the introduction of *A. melanocarpa* into the *Querco robori-Pinetum* association does not lead to the suppression of the native herb layer. instead. the bilberry maintains its dominance (25–60% cover). coexisting with the introduced shrub.

A critical aspect of this synergy is the shared reliance on mycorrhizal networks. As established by Read and Stribley (1973) and further elaborated by Cai et al. (2021). the ericoid mycorrhiza (ERM) of *Vaccinium* species is essential for nutrient cycling in nutrient-poor Polesie soils. The presence of similar fungal associates in *Aronia* stands suggests a non-competitive underground interaction. where the established fungal mycelium may even facilitate the stabilization of the introduced species within the forest's biogeochemical cycle.

Furthermore. the lack of invasive behavior in *Aronia melanocarpa*. as evidenced by its stable reproductive strategy involving both sexual and apomictic pathways (Mahoney et al.. 2019. Brand et al.. 2022). ensures that its integration into the Emerald Network habitats (UA0000133 "Horodnianskyi") remains ecologically safe. The maintenance of high canopy closure (0.6–0.7) and the conservation of diagnostic species like *Melampyrum pratense* and *Trientalis europaea* under the *Aronia melanocarpa* canopy prove that the forest ecosystem preserves its primary boreal-nemoral structure. Thus. the eco-cenotic compatibility of these species allows for a "dual-resource" management model where the native bilberry thrives as an edificator of the lower synpholia. while *Aronia* provides a high-yield secondary shrub layer without compromising regional biodiversity.

4.2 Resource resilience and the "dual-resource" strategy

The comparative analysis of the yield capacity of *Vaccinium myrtillus* and *Aronia melanocarpa* provides a compelling economic justification for the "dual-resource" management model in the Eastern Polesie. Our findings indicate a profound difference in productivity levels: while the native bilberry in its ecological optimum (*Molinio-Pinetum*) produces up to 550 kg/ha. the intensified forest plantations of *A. melanocarpa* reach a significant output of 5.000 kg/ha (50 c/ha). This tenfold difference highlights the potential of introduced species to alleviate the economic pressure on forestry enterprises while preserving the natural ecosystem (Gurčík et al.. 2023).

The success of *A. melanocarpa* in the Nevklia forestry is attributed to the optimized technological planting schemes. As demonstrated in our results. the high-density model (2x1.5 m) not only maximizes yield but also induces a specific physiological resilience. The early cessation of shoot growth in dense plantings facilitates superior wood maturation and shifts metabolic resources toward the development of flower buds (Ekiert et al.. 2021). This adaptation. combined with enhanced snow accumulation in dense stands. ensures high winter hardiness–a critical factor for the stability of forest bio-resources under the fluctuating climatic conditions of Northern Ukraine.

Conversely. the resource resilience of *V. myrtillus* is based on its extensive distribution across large. stable forest massifs. such as the Tupychiv forestry. where the total area of identified plots exceeds 317 hectares. Unlike the intensive plantation model of *Aronia*. bilberry management relies on the preservation of the forest's primary structure. The stable. uniform-regular distribution of *V. myrtillus* in these areas allows for organized industrial harvesting without the need for high-cost agricultural interventions. However. the sensitivity of bilberry to anthropogenic stress necessitates a "low-impact" management approach. including carefully timed winter sanitary cuttings to minimize damage to the berry layer (Kislitsina et al.. 2021).

By integrating the harvesting of wild *V. myrtillus* with the intensive cultivation of *A. melanocarpa*. forestry enterprises achieve economic diversification. This strategy mitigates the risks associated with natural yield fluctuations in wild populations and creates a high-value production line for the functional food market (Petković et al.. 2021). all while maintaining the ecological integrity of the Polesie forest fund.

4.3 Ecological safety and biodiversity conservation within the emerald network

The strategic integration of *Aronia melanocarpa* into the forest landscapes of Eastern Polesie raises the fundamental question of ecological safety within protected areas. Our research. conducted within the boundaries of the Emerald Network (UA0000133 "Horodnianskyi"). provides strong empirical evidence that *A. melanocarpa* plantations do not act as a driver of biodiversity loss. On the contrary. the structural complexity of these plantations facilitates the preservation of rare and endangered species. aligning with the EU Biodiversity Strategy for 2030 (European Commission. 2020).

The most significant finding in our phytosociological surveys was the consistent presence of rare species directly within the *Aronia melanocarpa* stands. These include *Platanthera bifolia*. *Epipactis helleborine*. and *Lilium martagon*. all of which are protected under the Red Data Book of Ukraine (Didukh. 2009). Furthermore. all identified orchid species (*Orchidaceae*) are included in Appendix II of the CITES Convention (2023). which imposes international monitoring on their populations to prevent overexploitation.

The high frequency of *P. bifolia* in 50% of the studied intensive plots (shrub cover 75–90%) contradicts the traditional view of introduced shrubs as inhibitors of native orchids. We argue that the specialized management of *Aronia* plantations–characterized by periodic thinning and the maintenance of a semi-shaded light regime–prevents the excessive accumulation of forest litter and the overgrowth of aggressive expansive grasses. thereby creating a favorable micro-refugium for these sensitive species (Mahoney et al.. 2019). The presence of CITES-listed species within managed forest areas proves that *A. melanocarpa* cultivation is harmonized with the strictest international conservation requirements.

Furthermore. the floristic integrity of the *Vaccinio-Piceetea* class is maintained under the *Aronia* canopy. The preservation of diagnostic boreal elements. such as *Melampyrum pratense* and the moss *Pleurozium schreberi*. proves that the introduction of *A. melanocarpa* does not cause a "syntaxonomic shift" or the ruderalization of the community. In contrast to invasive species like *Acer negundo* or *Robinia pseudoacacia*. which radically transform the soil chemistry and light conditions. *A. melanocarpa* exhibits high biocenotic loyalty. This is attributed to its non-aggressive reproductive strategy (Brand et al.. 2022) and its functional similarity to native understory components (Ekiert et al.. 2021). Therefore. the "dual-resource" model in the Eastern Polesie ensures that forestry enterprises can fulfill their economic goals while strictly adhering to the Bern Convention requirements for habitat conservation.

4.4 Verification of safety: compliance with international standards

The transition of forest bio-resources from the Eastern Polesie into the high-value pharmaceutical and functional food sectors is fundamentally dependent on their toxicological purity. Our comparative analysis of lead (Pb) and cadmium (Cd) accumulation in *Vaccinium myrtillus* and *Aronia melanocarpa* provides a robust verification of compliance with the global safety benchmarks established by the Codex

Alimentarius Commission (2025) in its General Standard for Contaminants and Toxins in Food and Feed (CXS 193-1995).

According to the Codex Alimentarius (CXS 193-1995). the maximum levels (MLs) for berries and other small fruits are set at 0.1 mg/kg for Pb and 0.05 mg/kg for Cd. calculated on a fresh weight basis. Our findings. presented in dry weight. show lead concentrations in fruits at 0.030–0.033 mg/kg. which. when converted to fresh weight (accounting for the average 75–80% moisture content of berries). are approximately 10–15 times lower than the international limit. Similarly. the cadmium levels in *V. myrtillus* (0.008 mg/kg dry weight) are negligible. while in *A. melanocarpa* (0.065 mg/kg dry weight). the fresh-weight equivalent remains safely below the 0.05 mg/kg threshold.

A critical observation is the selective accumulation patterns: *V. myrtillus* exhibits a statistically significant higher affinity for Pb in its leaves (0.128 mg/kg dw. $p < 0.01$). while *A. melanocarpa* selectively accumulates Cd in its fruits ($p < 0.001$). Despite these variations. the results confirm the Eastern Polesie as an exemplary "clean zone" under the WHO Guidelines on GACP (World Health Organization. 2003). For forestry enterprises. this high degree of safety. verified through rigorous *Mean* ± *SD* statistical analysis. serves as a primary regulatory tool for the international certification of non-timber forest products. Consequently. the ecological management of these species in the Eastern Polesie ensures that the raw materials meet the most stringent requirements of the Joint FAO/WHO Food Standards Programme (2025).

4.5 Ecological management perspectives for forest resources in eastern polesie

The synthesis of phytoecological. resource. and ecotoxicological data allows for the formulation of a strategic model for the ecological management of forestry enterprises in the Eastern Polesie. This model is based on the synergy between the conservation of natural biodiversity and the intensive production of high-value bio-resources.

4.5.1 Optimization of natural and cultivated resources

To ensure economic stability. enterprises should implement a "dual-resource" strategy. In large. stable massifs such as the Tupychiv forestry. management should focus on the sustainable harvesting of wild *Vaccinium myrtillus*. Given the high sensitivity of bilberries to anthropogenic stress (Itsoil=0.45). it is recommended to conduct all forestry interventions. including sanitary cuttings in compartments affected by root rot (e.g.. Comp. 80. 83). exclusively during the winter period. This minimizes mechanical damage to the berry layer and preserves the soil-mycorrhizal complex. Conversely. in forestries with fragmented resources like Nevklia. the expansion of intensive *Aronia melanocarpa* plantations (using 2×1.5 m schemes) is advised. The documented yield of 5.0 t/ha provides a high economic return while acting as a biological buffer against ruderalization.

4.5.2 Compliance with European safety and quality standards

The exceptional purity of the berries and shoots (Pb: 0.030–0.033 mg/kg). which is 10–15 times lower than the limits set by Codex Alimentarius (CXS 193-1995. 2025). serves as a primary regulatory asset. Forestry enterprises should utilize these ecotoxicological parameters for the international certification of their products under the WHO GACP guidelines. This transformation from "raw material supplier" to "certified bio-resource producer" is essential for entering the EU pharmaceutical and functional food markets.

4.5.3 Preservation of the emerald network integrity

The ecological management of these species must strictly adhere to the Bern Convention and the EU Biodiversity Strategy for 2030 (European Commission. 2020). Our discovery of rare orchids (*Platanthera bifolia*. *Epipactis helleborine*) and other CITES-listed species within managed forest areas proves that the "semi-cultural" cultivation of *Aronia melanocarpa* is harmonized with conservation goals. Maintaining a canopy closure of **0.6–0.7** and preventing forest cluttering through targeted thinning not only supports high berry yields but also creates micro-refugia for protected flora. Thus. the proposed management system for the Eastern Polesie ensures a balance between intensive resource utilization and the uncompromising preservation of the region's unique forest biodiversity.

5 CONCLUSIONS

Vaccinium myrtillus in the Eastern Polesie exhibits high ecological plasticity. acting as a dominant edificator across a wide syntaxonomic range. from moist boreal forests (*Molinio-Pinetum*) to complex oak-pine subors (*Querco robori-Pinetum*). The high floristic integrity of these communities and the presence of rare species (*Platanthera bifolia*. *Lycopodium annotinum*) confirm the exceptional conservation value of the study area within the Emerald Network.

A significant difference in productivity was established between natural and cultivated resources. While the maximum biological yield of native bilberry reaches 550 kg/ha. the intensified forest plantations of *Aronia melanocarpa* (using 2×1.5 m schemes) produce up to 5.000 kg/ha. This tenfold increase in efficiency provides a scientifically grounded basis for the "dual-resource" strategy to enhance the economic resilience of forestry enterprises.

It was proven that *A. melanocarpa* is an ecologically safe introduced species for the Polesie forest ecosystems. Its integration into the understory does not suppress native flora. instead. managed plantations act as micro-refugia for protected orchids listed in the Red Data Book of Ukraine and CITES Appendix II. ensuring compliance with the EU Biodiversity Strategy for 2030.

The heavy metal content in berries and shoots (Pb: 0.030–0.033 mg/kg) is 10–15 times lower than the maximum levels (MLs) established by the Codex Alimentarius (CXS 193-1995. 2025). This confirms the status of the Eastern Polesie as an exemplary "clean zone." enabling the international certification of its forest bio-resources for the global pharmaceutical and functional food markets.

Sustainable forest management should prioritize winter-only sanitary cuttings to protect the berry layer of *V. myrtillus* and the expansion of *A. melanocarpa* plantations in suitable forest types (B3 DS. C2-C3 GD). This integrated approach ensures a balance between intensive economic utilization and the uncompromising preservation of regional biodiversity.

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Authors' Contribution

All authors contributed equally to the development of this article.

Data availability

All datasets relevant to this study's findings are fully available within the article.

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