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The European semiconductor ecosystem: Regional development in a geopolitical context

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ABSTRACT: Human society is increasingly dependent on electronic devices, from phones and laptops to renewable energy and electric vehicles. Semiconductors are essential materials for these devices due to their electrical properties. The manufacture of semiconductors, such as chips, is one of the most complex and sophisticated processes in the manufacturing industry and requires numerous precision steps and many actors involved. This research aimed to analyse the European semiconductor ecosystem in terms of its regional development, Europe's position in the supply chain and the measures taken to reduce dependence on external markets. The results show a diversified but unbalanced European semiconductor ecosystem, with research and development activities in almost all European countries, but the production of semiconductor equipment and devices is concentrated in a few countries in central and western Europe. It also shows that Europe's dependence on external markets for semiconductor supplies is considerable and, although significant measures have been adopted to support the European semiconductor ecosystem, achieving the objectives proposed by the EU Chips Act will be difficult to achieve.

KEYWORDS: Europe, semiconductor ecosystem, dependence, EU Chips Act, global chip market

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1. INTRODUCTION

A semiconductor is a material with an electrical conductivity that lies between that of a conductor and that of an insulator. This unique property allows for precise control of electric current, making semiconductors the fundamental material for almost all modern electronic devices. Their key function is the ability to control the flow of electric current. Pure semiconductor materials are poor conductors, but their conductivity can be adjusted by adding impurities (doping) or by changing the temperature. They are doped with elements with three valence electrons (trivalent, e.g. boron), to create P-type semiconductors, or with five valence electrons (pentavalent, e.g. phosphorus), to create N-type semiconductors (Streetman, 2002; Tolasa, 2025).

Semiconductors are classified according to their composition, but also according to the way they conduct electric current. Depending on their composition, semiconductors can be elementary, compound, organic or layered. Elementary semiconductors are made up of a single chemical element, such as: silicon (the most widespread and used material in modern microchip technology, due to its stability and abundance), germanium (used for specialized circuits), carbon, selenium, tellurium or tin. Compound semiconductors are made up of several chemical elements: gallium arsenide (GaAs), gallium nitride (GaN), copper indium diselenide (CuInSe2), silicon carbide (SiC), indium phosphide (InP) or alloys of aluminum, gallium and indium. Organic semiconductors include amorphous or liquid semiconductor materials, and layered semiconductors have a layer-type structure. Depending on how they conduct electric current, semiconductors are intrinsic (without impurities) and extrinsic (semiconductors doped with controlled

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impurities to modify their electrical properties), the latter being the most common in applications (Streetman, 2002; Bird, 2002; Spain & Venkatanarayanan, 2014; Poplavko, 2019; Terna et al., 2021).

Semiconductor manufacturing is one of the most complex and sophisticated industrial processes, requiring hundreds of high-precision manufacturing steps to transform raw semiconductor material into the chips that power electronic devices. At the most basic level, sand is used to make ultra-pure silicon. The refined material is melted into single-crystalline cylindrical ingots and cut into very thin, flat discs called wafers, less than a millimeter thick and up to 300 mm in diameter. These wafers are polished to extreme smoothness and then coated with thin films of conductive, insulating or semiconducting materials (the deposition step), including a photosensitive layer called photoresist. This is followed by lithography, a crucial step in the chip manufacturing process, which transfers the complex chip design patterns onto the wafers, followed by etching and ion implantation (doping). Finally, the wafers are cut into individual chips (some wafers can contain thousands of chips), tested, and packaged. Hundreds of tests and measurements are performed to ensure the functionality of the products (Ruberti, 2023; Cerutti & Nardo, 2023; ESIA, 2025a).

In general, four major stages are distinguished within the semiconductor industry: research and development, design, manufacturing and assembly, testing and packaging. Only large players are integrated device manufacturers (IDM), which design and manufacture using their own intellectual property: Intel, Micron and Texas Instruments in the US or Samsung and SK Hynix in South Korea. There are many companies that specialize only in design, called fabless (Nvidia, Broadcom, Qualcomm or Apple, all in the US, MediaTek, Novatek and Realtek in Taiwan), and those that carry out only manufacturing activities are known as foundries (TSMC and UMC in Taiwan, GlobalFoundries in the United States or SMIC in China). Some companies specialize in manufacturing equipment (such as ASML in the Netherlands or Applied Materials and Lam Research in the USA), assembly, testing and packaging (Amkor in the USA, ASE in Taiwan, JCET in China or UTAC in Singapore), electronic design automation (Cadence and Synopsys in the USA and Siemens EDA in Germany) or Core Intellectual Property (Arm in the UK)(Poitiers & Weil, 2021; Bown & Wang, 2024; Huggins et al., 2023).

Semiconductors are essential components for numerous electronic products in various fields: consumer electronics, transportation, healthcare, renewable energy, communications, modern infrastructure, industry or defense (Bown & Wang, 2024; European Council, 2025a).

This research aimed in particular to analyse the European semiconductor ecosystem from the point of view of its regional development. The research also aimed to identify Europe's strengths in semiconductor manufacturing (such as holding key positions in the manufacturing process), as well as to compare it with other regions of the world. It also aimed to identify measures taken to reduce dependence on external markets and to implement them in order to achieve the assumed strategic objectives.

1.1. Historical context

The foundations of semiconductors were laid in the 19th century and the first half of the 20th century. In 1833, Michael Faraday discovered that the electrical conductivity of silver sulfide crystals increased with temperature, suggesting the properties of semiconductors. In 1874, Karl F. Braun discovered the rectifier effect at the point of contact between metals and certain crystalline materials, which allowed the conversion of alternating current to direct current. In 1901, Jagadis C. Bose patented a point-contact semiconductor rectifier for detecting radio waves. In December 1947, John Bardeen and Walter Brattain invented the germanium-based point-contact transistor, improved in 1948 by William Shockley, who developed the junction transistor (Computer History Museum, 2025).

The invention of the transistor led to the development of modern electronics. The introduction of the integrated circuit by Jack Kilby and Robert Noyce in the late 1950s marked another turning point. The miniaturization of electronic components enabled the mass production of increasingly complex devices (chips), leading to the subsequent microelectronics revolution (Tolasa, 2025). Today, innovation focuses on adding more and more components to smaller and smaller areas to increase processing performance and reduce power consumption. This is expressed in terms of “node size”, with smaller nodes indicating more advanced chips (Poitiers & Weil, 2021).

American companies have long dominated the semiconductor industry. Texas Instruments, National Semiconductors, Motorola, and Intel were among the top global players in 1980 (by revenue). While in Europe Philips has long been a major player in the sector, in Asia the first companies in the field emerged in Japan in the 1970s and 1980s, and then in Taiwan and South Korea. Taiwan Semiconductor Manufacturing Corporation (TSMC) emerged in 1987 as the world's first manufacturer of chips designed by other companies. The emergence of the foundry-less model profoundly changed the structure of the industry, with some companies focusing exclusively on chip design (Bown & Wang, 2024).

1.2. Geopolitical context

The semiconductor industry is undergoing a historic transformation, moving from a model based on global efficiency to one defined by national security and geopolitical competition. The geopolitical framework is marked by trade tensions between the US and China. Tariff policies and trade tensions between the US and China have forced a restructuring of supply chains, and US exports to China have declined sharply. Overall, in 2025, US exports of goods were 26% lower than in 2024. As a share of total US production, sales of goods and services to China had fallen to almost half of their 2017 levels (Bown, 2026). Europe has also faced more Chinese imports and higher US tariffs (Devesa et al., 2026). In the semiconductor sector, competition between the two countries has been manifested through US sanctions and export controls to limit China's role in the global chip supply chain. China has thus set out to create a fully Chinese semiconductor supply chain (Sharma, 2025). Directly affected, Europe's strategy has aimed to build a resilient semiconductor ecosystem, with the aim of increasing economic security by reducing dependence on external actors and ensuring a competitive advantage in the field.

2. LITERATURE REVIEW

The scientific literature on semiconductors is vast and addresses a wide range of issues, from technological and economic to geopolitical and sustainability. Some authors examine the influence of European policies on the development of the semiconductor industry and argue that the European semiconductor industry is at a crossroads due to the long-term decline in competitiveness and industry size (Johnston & Huggins, 2023). Others consider digital sovereignty as a tool for legitimizing trade, economic and research policies and assert the need for a strong semiconductor industry in the EU and the globalized nature of supply chain threats (Monsees, 2025). There are authors who have tried to identify the determinants and barriers to building resilience in the semiconductor supply chain, proposing possible scenarios for the year 2050 (Ejdys & Szpilko, 2023). The decline of the European semiconductor industry is also explained by the dominance of demand for consumer electronics, the structure of demand being one of the main factors affecting the rate and direction of technological change and the evolution of high-tech industries (Malerba, 1985).

Aspects targeting the sustainability of the semiconductor industry have also been widely addressed (Song & Dong, 2024; Liu et al., 2024; Qi et al., 2024; Narayanaswamy & Muthusamy, 2011). For example, some authors have focused on understanding how semiconductor research and technology organizations promote sustainability and sustainability-oriented innovations, as the semiconductor industry consumes large amounts of energy, electricity, and water and generates hazardous waste and greenhouse gas emissions (Konstari & Valkokari, 2025).

Many authors analyze the semiconductor industry in a geopolitical context (Bown, 2020; Miller, 2022) and emphasize the dominance of the global value chain and strong extraterritorial control of the United States (Malkin & He, 2024). The fact that states seek to expand their control over the semiconductor value chain, while reducing their dependence on foreign production, is emphasized by some authors (Malkin & He, 2024; Kim & Rho, 2024). Wong et al. (2024) examined the changing landscape of global value chains and competition in the semiconductor industry as the United States implements chokepoint measures to limit the growth of semiconductor production in China. The authors found that these measures will have significant impacts, particularly on three types of memory (HBM, DRAM, and NAND) and logic chips, and will slow down the speed and process of China’s catch-up. Another study addresses the threats posed by geopolitical and climate risks that are undermining the resilience of the global semiconductor supply chain, noting that companies' profits have declined significantly due to disruptions and delays in chip supply. The study provides theoretical and managerial insights for resilient supply chain management (Zhang et al., 2024).

3. DATA AND METHODS

In the current geopolitical context, the development of the European semiconductor system is defined by the transition from global dependence to strategic autonomy. Spatially, the research focuses on the European space, but highlights the relationship with other geographical areas, such as East Asia and the SAU. The temporal framework follows the situation of the European semiconductor ecosystem from the relatively recent past (2020-2023), marked by the semiconductor crisis and the implementation of the European Chips Act, to the present.

This research uses quantitative and qualitative methods to collect and analyze data on the European semiconductor ecosystem. Data on the composition of the European semiconductor ecosystem was compiled from various sources, mainly the official websites of research institutions and companies operating in the field. The documentation aimed to identify the main actors involved in the semiconductor field in Europe and group them according to the activity carried out: research and development, production of basic materials, production of equipment used in the chip manufacturing process or production of semiconductor devices. The data obtained were summarized in the form of tables.

In identifying the main players in the semiconductor field, technological performance (such as the ability to design or manufacture chips at advanced nodes), market dominance (control of market segments, such as essential equipment or devices) or financial (such as revenue and market share) were taken into account. In research and development, those research institutions or companies that have a clear commitment to innovation, are distinguished by technological capabilities, financial investments and influence within the global ecosystem were targeted. In general, key players are those that have the ability to drive the industry, control a significant market share or provide essential technologies.

For regional differentiation, the research followed the geographical location of research or production units. Other data used in the research come from international sources and databases (Semiconductor Industry Association, European Council, European Commission, European Semiconductor Industry Association), but also from consulting a specialized bibliography and other sources. To highlight the regional distribution of the European semiconductor ecosystem or the evolution of some indicators, graphical methods were used and the results were subsequently interpreted.

4. RESULTS

Within the global semiconductor ecosystem, Europe has significant R&D capabilities, is a major supplier of chip manufacturing equipment and has a highly specialised semiconductor device industry, such as chip production for the automotive, aerospace, defence and security, and industrial sectors. Europe has a top-notch education system that produces talent and a robust R&D ecosystem, including Imec in Belgium, the Fraunhofer Institutes in Germany, and CEA-Leti in France. Also, the British company Arm designs the chip architecture (the structural design and organization of integrated circuits within a chip) for the world's largest computing ecosystem (over 325 billion devices contain Arm-based chips). Their architecture is prevalent in most smartphones, but is also present in many other areas (Arm, 2025).

European companies are world leaders in the production of highly sophisticated equipment needed to manufacture chips. For example, ASML (Netherlands) is the world's only manufacturer of extreme ultraviolet (EUV) lithography machines, essential for manufacturing the world's most advanced chips. Their lithography systems offer the highest resolution in high-volume production, allowing chipmakers to include more transistors on a single chip (ASML, 2026). Other European companies are leaders in areas such as vacuum technology (Edwards Vacuum), optics (Carl Zeiss) or wafer bonding equipment (EV Group, SÜSS MicroTec).

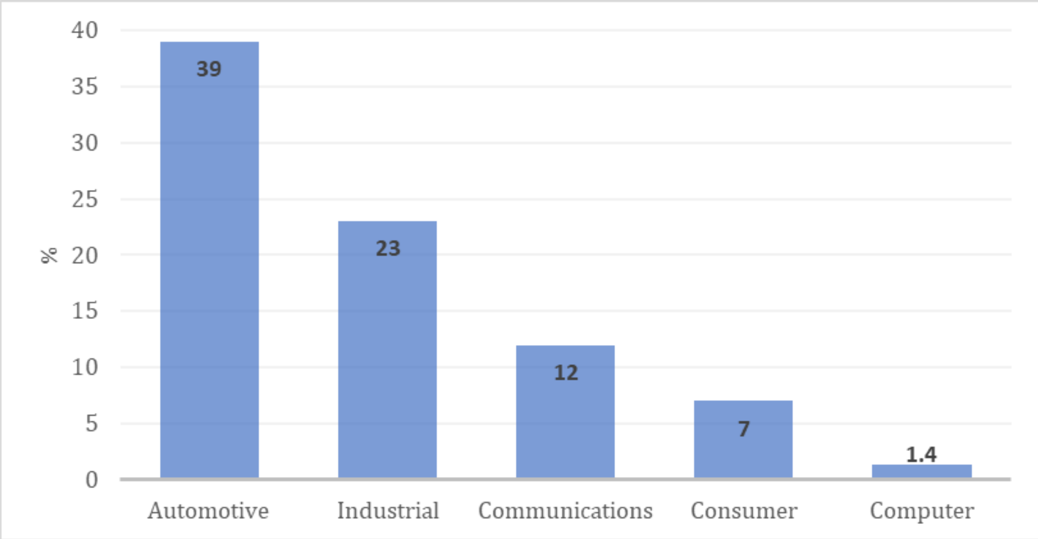

Figure 1. EU end-user semiconductor device market share in 2023.
Source: European Council (2025b).

In the production of semiconductor devices, Europe excels in specialized areas that require high reliability and unique engineering. The automotive sector is the main destination for chips produced in Europe (European Council, 2025b) (Figure 1). Infineon Technologies and STMicroelectronics are major players in the field of power electronics, sensors and microcontrollers. Europe is also important in the design and production of "More than Moore" components (sensors, power and telecommunications components), crucial for the automotive industry, defense, healthcare and other emerging technologies (Dauvé, 2025). Among the leading European companies in the production of "More than Moore" components are STMicroelectronics, Infineon Technologies, NXP Semiconductors or Robert Bosch GmbH, which are also the major European integrated device manufacturers (IDM).

It is difficult to estimate the total size of the European semiconductor ecosystem. It is estimated that there are at least 2000 companies active in the processes, development and production of semiconductors (Huggins et al., 2023). In general, there are few large companies in the semiconductor industry, and most of them are American (Nvidia, Broadcom, Intel, Qualcomm, Micron Technology, AMD, Applied Materials, Lam Research, Texas Instruments, Analog Devices) or Asian (Samsung Electronics, TSMC, SK Hynix, ASE Group, MediaTek, KLA, TEL, Sony). Among the European companies, the most important are: ASML, Infineon Technologies, NXP Semiconductors, STMicroelectronics or Arm (Table 1).

Table 1. Major companies in the semiconductor industry in Europe.

Company	Headquarters	Locations in Europe	Areas of activity
ASML	Veldhoven (Netherlands)	Veldhoven, Delft, Oirschot, Berlin, Dresden, Erlangen, Leuven, Crolles, Avezzano	Lithography systems for chip production
Infineon Technologies	Neubiberg (near Munich, Germany)	Dresden, Regensburg, Warstein, Augsburg, Duisburg, Erlangen, Ilmenau, Langen, Soest, Villach, Cegléd, Graz, Klagenfurt, Linz, Le Puy-Sainte Réparade, Zurich, Stockholm, Cork, Dublin, Padua, Pavia, Bristol, Redhill, Brașov, Bucharest, Iași, Belgrad, Budapest, Cegléd, Lviv	Automotive, power & sensor systems, green industrial power, connected secure systems
NXP Semiconductors	Eindhoven (Netherlands)	Nijmegen, Delft, Dresden, Munich, Hamburg, Gratkorn, Leuven, Toulouse, Caen, Mougins, Milan, Catania, Glasgow, Southampton, Stockholm, Rožnov pod Radhoštěm, Bucharest, Sibiu, Budapest	Automotive, IoT, and secure connectivity chips.
STMicroelectronics	Geneva (Switzerland)	Crolles, Rousset, Tours, Rennes, Agrate Brianza, Catania, Marcianise, Kirkop, Norrköping	Automotive, Industrial & Power, IoT & Communications.
Arm	Cambridge (United Kingdom)	Cambridge, Manchester, Bristol, Sheffield, Sophia Antipolis, Aschheim, Lund, Galway, Oslo, Trondheim, Budapest, Sentjernej	Semiconductor intellectual property (IP) and architecture licensing.

ASM International	Almere (Netherlands)	Almere, Leuven, Helsinki	Wafer processing equipment (ALD/Epitaxy)
BE Semiconductor Industries (Besi)	Duiven (Netherlands)	Duiven, 's-Hertogenbosch, Steinhausen, Radfeld	Advanced packaging and assembly equipment
Technoprobe	Cernusco Lombardone (Italy)	Cernusco Lombardone, Agrate Brianza, Osnago, Vimercate, Catania	Wafer testing and probe card technology.
Soitec	Bernin (France)	Bernin, Grenoble, Besançon, Hasselt, Le Bourget-du-Lac	Engineered substrate materials (SOI wafers)
Melexis	Ypres (Belgium)	Ypres, Tessenderlo, Sofia, Erfurt, Dresden, Düsseldorf, Sophia Antipolis, Corbeil-Essonnes, Courbevoie, Bevaix, Kyiv	Mixed-signal automotive sensor ICs

Source: ASML, 2026; Infineon, 2024; NXP, 2026; STMicroelectronics, 2026; Arm, 2025; ASM International, 2022; BESI, 2026; Technoprobe, 2025; Soitec, 2026; Melexis, 2026.

4.1. Semiconductor research and development in Europe

The main component of the European semiconductor ecosystem is research and development, including advanced chip design, which aims to: achieve technological sovereignty, stimulate innovation in artificial intelligence, IoT or 5G, improve manufacturing processes, secure supply chains and build a skilled workforce. The achievement of these goals is strongly supported by initiatives such as the European Chips Act and the Chips JU (CjipsJU, 2025).

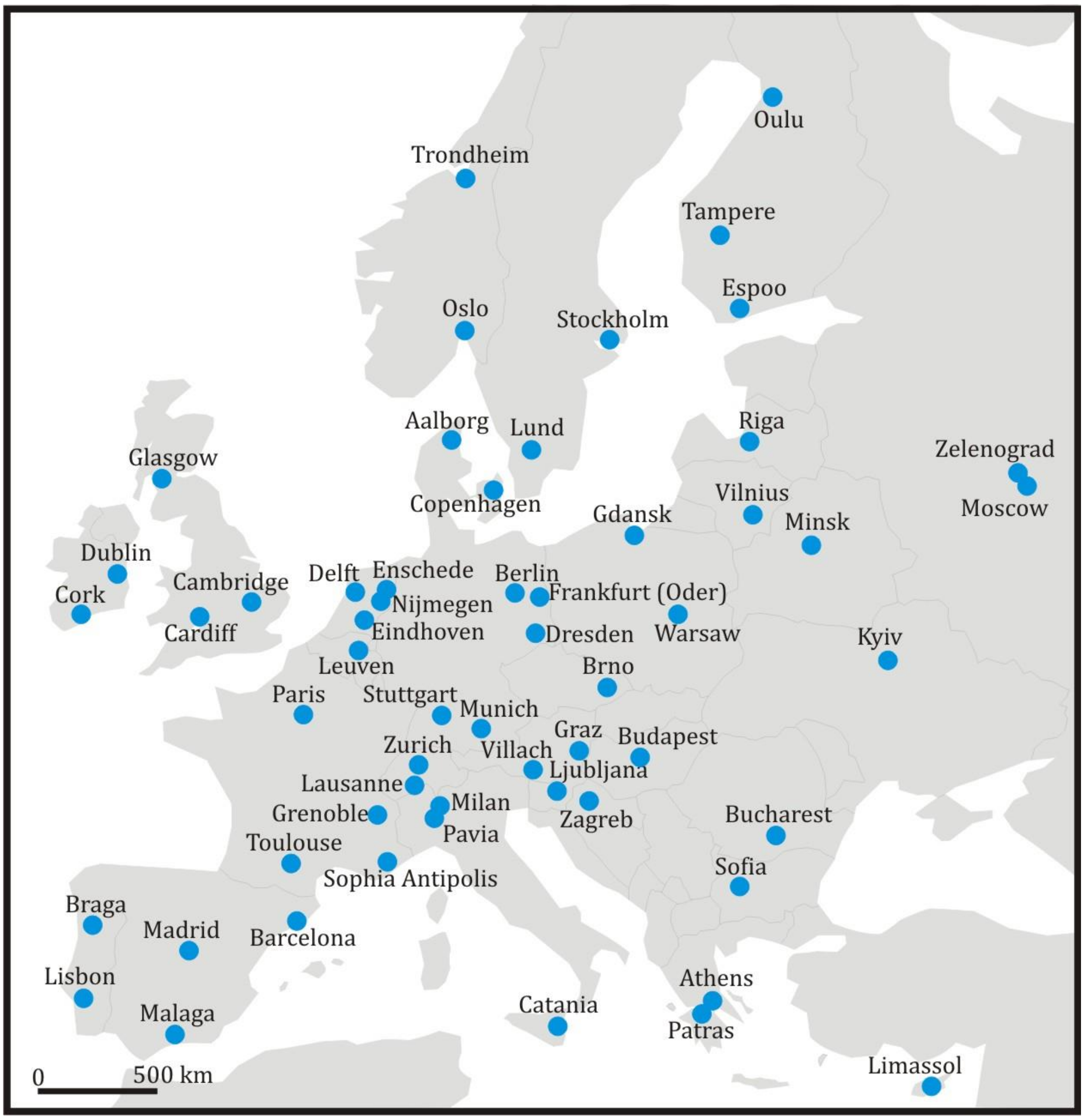

Figure 2. Main centers in semiconductor R&D in Europe.

The research and development component in the field is distributed throughout Europe (Figure 2), but is better developed in some countries such as Germany, Belgium, the Netherlands, France or the United Kingdom. The world's largest independent research and innovation center for nanoelectronics and digital technology is located in Leuven (Belgium). This is Imec (Interuniversity Microelectronics Centre), which has state-of-the-art facilities, including a 300 mm semiconductor pilot line, clean rooms and laboratories, essential for innovation, and collaborates with industrial partners, startups and numerous universities. Although headquartered in Leuven, Imec operates globally, with a presence in Europe in the Netherlands, the United Kingdom, Spain, Germany and Italy (Imec, 2026).

Germany stands out for its large number of R&D players in the semiconductor industry, particularly in the city of Dresden, also known as Silicon Saxony. The region is home to many key players, including the Dresden University of Technology, several Fraunhofer institutes (such as the Fraunhofer Institute for Photonic Microsystems) and major companies such as Infineon Technologies, GlobalFoundries, Bosch, X-FAB, NXP or Carl Zeiss SMT (Silicon Saxony, 2023). Infineon, the most powerful company in the field in Germany, had over 13,200 R&D employees worldwide at the end of 2024, in 71 R&D centers in 27 countries. In Europe, there were 30 centers, of which 10 were in Germany, 4 in Austria, 3 in Romania, two each in Ireland, Italy, Hungary and the United Kingdom and one each in France, Sweden, Switzerland, Serbia and Ukraine (Infineon Technologies AG, 2024).

A strong R&D ecosystem in the field is also located in the Netherlands. The Brainport Eindhoven region, which includes the Eindhoven University of Technology (with the Casimir Institute), the ASML campus in Veldhoven and the headquarters of NXP Semiconductors, is noteworthy. Also important are the University of Twente (MESA+ Institute for Nanotechnology) in Enschede and TU Delft and QuTech in Delft (NFIA, 2024). France also makes an important contribution in this field, with the Grenoble region being the most prominent. It is home to CEA-Leti (Laboratoire d'électronique des technologies de l'information), one of the world's largest organizations for applied research in microelectronics and nanotechnology. CEA-Leti has created numerous startups and laid the foundations for the microelectronics sector in France (CEA-Leti, 2026). STMicroelectronics and Soitec also have R&D facilities in Grenoble.

Significant semiconductor R&D activities are also taking place in the UK, Italy, Sweden, Poland, Austria, Finland, and others (Table 2). The UK has major initiatives focused on compound semiconductors (in Cardiff), photonics and chip design, and the University of Cambridge is a leading centre for semiconductor design, being the headquarters of Arm (techUK, 2025). In Italy, important centres are in Lombardy, including Fondazione Chips-IT and Politehnico di Milano. The Franco-Italian company STMicroelectronics has R&D facilities in Catania and Agrate Brianza (The Italian House of Business, 2026). In Poland, Pomerania is emerging as a critical centre for semiconductors, hosting major companies such as Intel, SK Hynix and Synopsys. Intel has the largest R&D technology centre in Europe in Gdańsk, with around 3000 employees, and one of the largest of its kind in the world, with a main focus on software development (Tek.info.pl., 2025). Kista Science City is a major technology center in Stockholm, home to universities, research institutes and technology companies, including Stockholm University, the Royal Institute of Technology, the Research Institutes of Sweden and the Swedish Defence Research Agency (Kista Science City, 2026).

Table 2. Major players in semiconductor research and development in Europe.

Country	Main locations	Major players	
		Academic and research institutes	**Companies with R&D activities**
Austria	Villach, Graz, Linz	Silicon Austria Labs (SAL), Graz University of Technology	Infineon, NXP, Lam Research
Belgium	Leuven, Ghent, Louvain	Imec (Interuniversity Microelectronics Centre), Ghent University, UCLouvain	Melexis, NXP, X-FAB, Keysight
Czech Republic	Brno	Brno University of Technology	Onsemi, Codasip, Elmos Semiconductor, TESCAN
Denmark	Copenhagen, Aalborg	DTU Nanolab (Technical University of Denmark), Niels Bohr Institute (University of Copenhagen), Aalborg University	Samsung, NVIDIA, Lotus Microsystems
Finland	Espoo, Tampere, Oulu	InstituteQ (The Finnish Quantum Institute), VTT Technical Research Center of Finland, Aalto	IQM Quantum Computers, SemiQon

		University, Micronova, University of Tampere	
France	Grenoble, Sophia Antipolis, Paris, Toulouse	CEA-Leti (Laboratoire d'électronique des technologies de l'information), Minatec (Grenoble), C2N (Centre for Nanosciences and Nanotechnology), Paris-Saclay University, Laboratory for Analysis and Architecture of Systems (Toulouse)	STMicroelectronics, Soitec, MACOM, NXP, Microchip Technology
Germany	Dresden, Munich, Frankfurt (Oder), Stuttgart	Fraunhofer Institutes, Leibniz Institute for High Performance Microelectronics (Frankfurt an der Oder), Max Planck Semiconductor Laboratory (Munich), Dresden University of Technology, University of Stuttgart, TU Berlin	Infineon, GlobalFoundries, Bosch, X-FAB, NXP, Carl Zeiss SMT, Siltronic, AIXTRON
Ireland	Cork, Dublin	Tyndall National Institute, University College Dublin	Infineon, Qualcomm, Broadcom, Microchip Technology
Italy	Pavia, Milan, Catania	Fondazione Chips-IT in Pavia, Politecnico di Milano, Institute for Microelectronics and Microsystems of the National Research Council	STMicroelectronics
Netherlands	Eindhoven, Nijmegen, Enschede, Delft	Eindhoven University of Technology (Casimir Institute), University of Twente (MESA+ Institute), Delft University of Technology, Holst Centre, OnePlanet Research Center	ASML, NXP, BESI, Imec
Norway	Trondheim, Oslo	Norwegian University of Science and Technology, SINTEF MiNaLab (Oslo)	Nordic Semiconductor
Poland	Gdańsk, Warsaw	Gdańsk University of Technology, Łukasiewicz Research Network	Intel, SK Hynix, Synopsys
Portugal	Braga, Lisbon, Porto	International Iberian Nanotechnology Laboratory din Braga INESC Microsistemas e Nanotecnologias (Lisbon)	Synopsys, Amkor Technology
Romania	Bucharest	National Institute for Research and Development in Microtechnologies (hosts IMT-MINAFAB), POLITEHNICA Bucharest	Infineon, Microchip Technology, NXP
Russia	Zelenograd, Moscow, Sankt Petersburg	Molecular Electronics Research Institute (Zelenograd), Moscow Center for SPARC Technologies, Scientific Research Institute of Electronic Technology	Mikron Group (JSC Mikron), Angstrem, Baikal Electronics, GS Nanotech
Spain	Barcelona, Madrid, Malaga	Institute of Microelectronics of Barcelona, Institute of Micro and Nanotechnology of Madrid	Imec, Intel, Cisco
Sweden	Stockholm, Lund, Linköping	Stockholm University, Royal Institute of Technology, Research Institutes of Sweden, Electrum Laboratory, Lund University	Ericsson, STMicroelectronics, Silex Microsystems, SweGaN
Switzerland	Zurich, Lausanne, Neuchâtel	Swiss Federal Institute of Technology in Zurich, École Polytechnique Fédérale de Lausanne, Swiss Center for Electronics and Microtechnology in Neuchâtel	STMicroelectronics, IBM Research, U-blox, Sensirion, EM Microelectronic
United Kingdom	Cambridge, Cardiff, Glasgow	University of Cambridge, Cardiff Compound Semiconductor Centre, University of Glasgow, University of Sheffield, University of Southampton	Arm, NVIDIA, Qualcomm, NXP, Infineon, Pragmatic Semiconductor, etc.

Source: ABA, 2023; Imec, 2026; CSIS, 2024; CSC, 2025; Silicon Saxony, 2023; Infineon, 2024; GTAI, 2024; NFIA, 2024; CEA-Leti, 2026; techUK, 2025; CC-NorChip, 2026; España Digital, 2023; POEMS, 2026; Semiconductor Sweden, 2026; Kista Science City, 2026; Tek.info.pl., 2025; DTN, 2026.

4.2. Production of wafers and other basic materials

In general, the semiconductor industry uses hundreds of materials. Semiconductor wafers, usually made of high-purity monocrystalline silicon, are the fundamental material (substrate) for the entire semiconductor industry, acting as the basis on which integrated circuits (chips) are made. Major European companies producing wafers from monocrystalline silicon ingots include Siltronic, Okmetic, Soitec, Topsil or MEMC Electronic Materials. Siltronic, a German company headquartered in Munich, is one of the world's leading producers of hyperpure silicon wafers, supporting the semiconductor supply chain in

Europe. It develops and produces wafers in Burghausen (large diameter wafers, up to 300 mm) and Freiberg (state-of-the-art 300 mm wafers) (Siltronic, 2026). Okmetic of Finland is the world's seventh largest supplier of customized 150 and 200 mm silicon wafers for MEMS sensors, radio frequency applications and power semiconductors, produced in its Vantaa plant (Okmetic, 2026).

In Bernin (near Grenoble), Soitec produces advanced semiconductor materials, in particular silicon-on-insulator (SOI) and silicon carbide (SiC) wafers, used in applications from smartphones to electric vehicles (Soitec, 2026). High-purity silicon ingots and wafers, including 200 mm wafers (used in power electronics, renewable energy and quantum computing), are produced in Frederikssund by Topsil (part of the GlobalWafers Group), the largest semiconductor company in Denmark. It is one of the few companies in the world capable of producing hyperpure silicon obtained by the Float Zone method (Topsil, 2026). The Italian company MEMC Electronic Materials (part of GlobalWafers) produces high-quality single crystal silicon ingots in Merano and polished and epitaxial wafers in Novara, used in the automotive, consumer electronics, telecommunications and defense sectors (GlobalWafers, 2026).

Other materials used in the semiconductor industry are also produced in Europe: high-quality silicon metal (key raw material for creating hyperpure silicon), silicon carbide (SiC) powders and granules, or high-purity gases and chemicals (Table 3).

Table 3. European semiconductor ecosystem – wafer production and other basic materials.

Company	Production centers	Products
Siltronic	Burghausen, Freiberg (Germany)	Monocrystalline silicon wafers
Okmetic	Vantaa (Finland)	Customized silicon wafers
Soitec	Bernin (France)	Silicon-on-Insulator (SOI) and Silicon Carbide (SiC) wafers
Topsil	Frederikssund (Denmark)	High purity silicon ingots and wafers, including 200 mm wafers
MEMC Electronic Materials	Merano, Novara (Italy)	Monocrystalline silicon ingots and polished and epitaxial wafers
X-FAB Silicon Foundries	Dresden (Germany)	Gallium nitride-on-silicon (GaN-on-Si) wafers
SweGaN AB	Linköping (Sweden)	GaN-on-SiC (gallium nitride on silicon carbide) epitaxial wafers
Littelfuse	Dortmund (Germany)	200 mm wafers
SiCrystal (part of Rohm)	Nuremberg (Germany)	Monocrystalline silicon carbide semiconductor wafers
Kepp EU	Riga (Latvia)	High purity silicon ingots
Wacker Chemie AG	Burghausen, Nünchritz (Germany)	Hyperpure polysilicon (world market leader)
Fiven ASA (part of Kymera Int.)	Lillesand, Arendal (Norway)	High purity silicon carbide (SiC) powders and granules (global leader)
SICREATE (part of EBNER Group)	Leonding (Austria)	High purity SiC powders
ESK-SIC GmbH	Frechen (Germany)	High purity SiC powders and granules
Elkem	Bremanger, Salten, Fiskaa (Norway), Roussillon, Saint-Fons (France), etc.	Advanced silicon-based materials
Zadient	Chambéry (France), Leipzig (Germany)	High purity source materials made by the chemical vapor deposition (CVD) process
PCC BakkiSilicon	Husavik (Iceland)	High-quality silicon metal (key raw material for creating ultrapure silicon)
BASF	Ludwigshafen (Germany)	High purity chemicals (including sulfuric acid, ammonium hydroxide) for wafer cleaning and etching processes
Air Liquide	Dresden (Germany)	Ultrapure gases (nitrogen, oxygen, hydrogen, helium, etc.) and advanced electronic materials (special molecules for nanoscale deposition) essential for the manufacture of semiconductors
Merk	Darmstadt (Germania)	High purity gases for deposition, etching, cleaning and doping processes

Source: GTAI, 2024; Siltronic, 2026; Okmetic, 2026; Soitec, 2026; Topsil, 2026; GlobalWafers, 2026; Wacker, 2026; INSIDE Magazines, 2025; Kymera Int., 2026; Elkem, 2026; Semiconductor Sweden, 2026; EBNER, 2026; BASF, 2025; Air Liquide, 2025; Merk, 2026.

4.3. Production of equipment needed in chip manufacturing

Chip production requires sophisticated equipment (deposition systems, lithography machines, etching systems, metrology and inspection instruments, assembly and packaging equipment), automated, housed in specialized clean rooms. High-precision instruments measure physical/electrical properties (metrology) and detect defects (inspection) at the nanoscale of the chips, ensuring quality control. Assembly and packaging equipment takes silicon chips and transforms them into usable components, covering processes such as die attachment, wire bonding, encapsulation or dicing.

The Netherlands is a major contributor to the design and production of advanced chip manufacturing equipment. Approximately 85% of chips manufactured globally use technology from the Netherlands. Brainport Eindhoven is the main semiconductor hub in the Netherlands and is home to ASML (with a production center in Veldhoven). ASML is the leading manufacturer of extreme ultraviolet (EUV) lithography machines, which are needed to manufacture the world's most advanced chips, with a market share of 90%. It is the largest semiconductor company in Europe by market value (275 billion euros) and employs around 39,000 people worldwide. The company also produces various key components for lithography systems in Berlin (wafer tables and clamps, reticle chucks and mirror blocks). BESI, headquartered in Duiven, is a global leader in semiconductor assembly and packaging solutions. It has four design and development centers in Europe, but series production has been outsourced to Asia (Malaysia and China). ASM International, another major equipment manufacturer, has 55% of the market for advanced atomic layer deposition technologies, but its volume production facilities are in Asia (ASML, 2026; NL Netherlands, 2025; ASM International, 2022). Also in the Netherlands, in Enschede, the American company Lam Research produces advanced pulsed laser deposition (PLD) technology and equipment for critical components used in 5G, MEMS and photonics applications (Lam Research, 2025).

Other important equipment manufacturers are Carl Zeiss SMT, TRUMPF or AIXTRON from Germany, Technoprobe SpA from Italy or EV Group from Austria (Table 4, Figure 3). Carl Zeiss SMT is the only manufacturer in the world of optics used in extreme ultraviolet lithography machines, and TRUMPF is the only manufacturer of lasers required for EUV lithography (Zeiss, 2020). AIXTRON also produces metal-organic chemical vapor deposition (MOCVD) equipment in Herzogenrath (near Aachen), Cambridge and Turin (AIXTRON, 2024). Technoprobe SpA specializes in the design and development of probe cards (high-tech devices that facilitate chip testing), with production facilities in Cernusco Lombardone, Agrate and Osnago (Technoprobe, 2025).

Table 4. European semiconductor ecosystem - equipment manufacturing.

Company	Production centers	Equipment type
ASML	Veldhoven (Netherlands), Berlin (Germany)	Extreme ultraviolet (EUV) lithography machines
Carl Zeiss SMT	Oberkochen (Germany)	Optics used in extreme ultraviolet lithography machines
AIXTRON	Herzogenrath (Germany), Cambridge (UK), Turin (Italy)	Metal-organic chemical vapor deposition equipment (MOCVD) (global leader)
SÜSS MicroTec	Garching, Sternenfels (Germany)	Versatile wafer bonding equipment
TRUMPF	Warsaw (Poland)	Laser systems (essential in semiconductor manufacturing machines)
Technoprobe SpA	Cernusco Lombardone, Agrate Brianza, Osnago (Italy)	Probe cards (chip testing devices)
SPEA	Volpiano (Italy)	Automated testing equipment for electronic devices
LPE (part of ASM Int.)	Baranzate (Italy)	Epitaxy equipment
EV Group	St. Florian am Inn (Austria)	Wafer bonding equipment (a global leader)
Lam Research	Enschede (Netherlands), Villach (Austria)	Advanced Pulsed Laser Deposition (PLD) equipment; Spin Clean Technology (for wafer cleaning, etching and stripping)
VIGO Photonics	Ożarów Mazowiecki (Poland)	Infrared photonics (plays a vital role in various stages of the semiconductor manufacturing and testing process)
AIUT	Gliwice (Poland)	It provides specialized equipment and solutions for

		automation, robotics and IoT
Edwards Vacuum	Clevedon (UK), Lutín (Czech Republic)	Abatement systems and integrated vacuum and purification systems
Oxford Instruments	Bristol (UK)	Plasma etch technologies and wafer processing
KLA	Newport (UK)	Specialized etch and deposition equipment
UnitySC	Grenoble (France)	Metrology and inspection (tools for detecting defects that can cause chip damage)
RIBER	Bezons (France)	Molecular beam epitaxy (MBE) systems and components
SET (Smart Equipment Technology)	Saint-Jeoire (France)	World leading supplier of High Accuracy Flip Chip Bonders and versatile Nanoimprint Lithography (NIL) solutions
VAT Group	Haag (Switzerland), Arad (Romania)	Vacuum valves (world leader)
Mycronic	Täby/Stockholm (Sweden)	High-precision production equipment (photomask production, advanced packaging and testing)
MSTECH Europe	Barcelona (Spain)	Back-end automation solutions, particularly depaneling equipment used in final assembly stages
ThermoFisher, Tescan	Brno (Czech Republic)	Advanced metrology and process control tools, such as electron microscopes

Source: NL Netherlands, 2025; ASML, 2026; ASM International, 2022; GTAI, 2024; Lam Research, 2025; Zeiss, 2020; AIXTRON, 2024; Technoprobe, 2025; Semiconductor Sweden, 2026; TRUMPF, 2026; VAT Group, 2026; LPE, 2022; Tek.info.pl., 2025; MSTECH Europe, 2026; CSC, 2025.

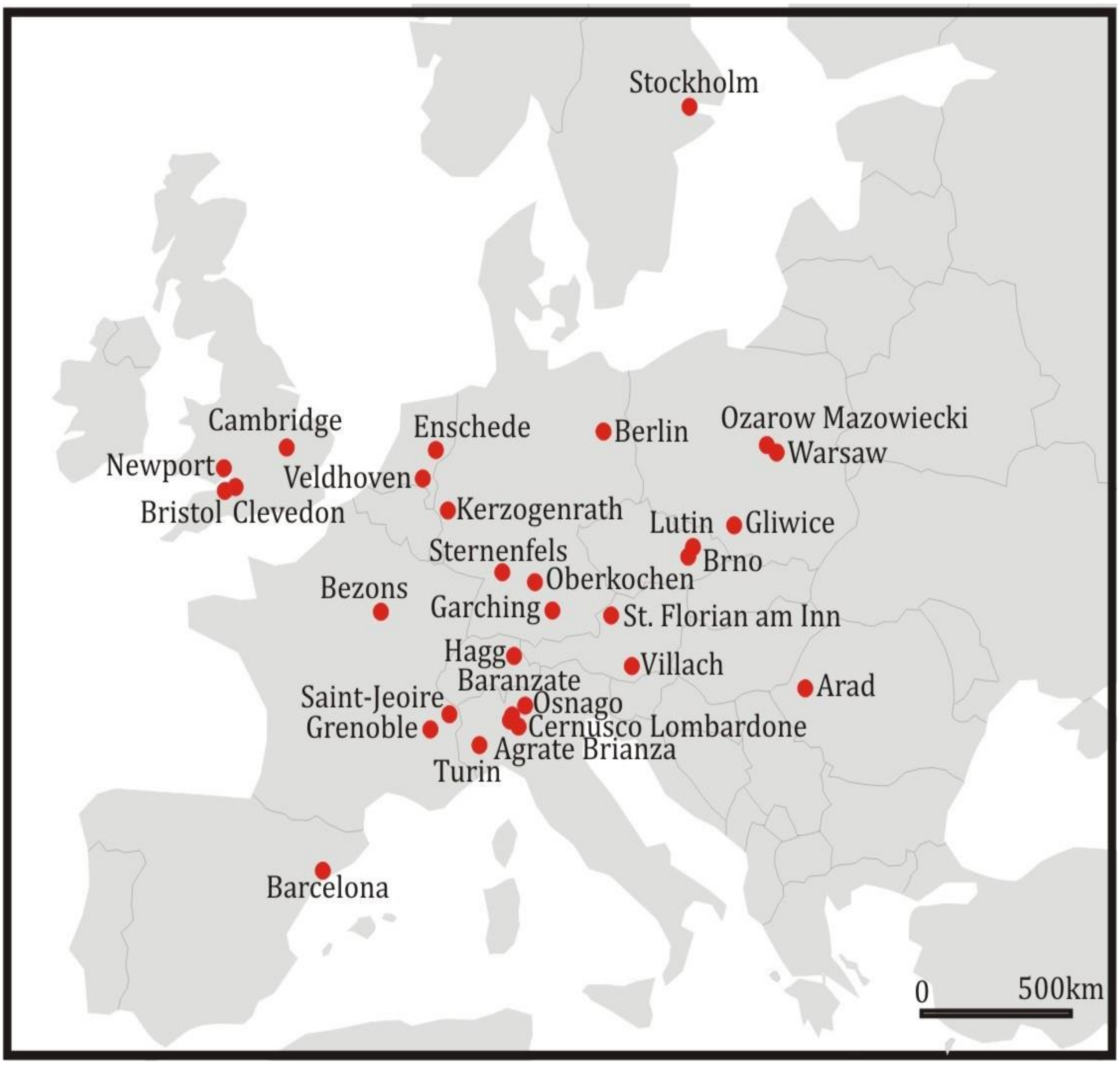

Figure 3. Equipment production centers for the manufacture of semiconductor devices.

4.4. Semiconductor device production

Semiconductor devices are electronic components found in almost all modern electronics. These devices are classified into two main types: discrete devices and integrated circuits. Discrete devices are individual components with a single dedicated function, such as transistors, diodes, or thyristors. Integrated circuits (ICs) are semiconductor devices that integrate multiple electronic components onto a single chip: microprocessors, memory chips, logic ICs, or analog ICs. Integrated circuits can contain millions or billions of transistors and other components packaged on a single piece of semiconductor material. There are also optical devices, such as LEDs (essential in communication systems), sensors and display technologies, microwave devices (used for radar applications, wireless communications or satellite transmissions) or sensors (detect changes in environmental conditions and convert them into electrical signals, being essential for applications in automotive systems, healthcare, industrial automation and consumer electronics (Takahashi, 2005; AIUT, 2025).

The European semiconductor device industry is mainly concentrated in Germany, followed by the Netherlands, France, the United Kingdom and Italy. European players such as NXP, Infineon and STMicroelectronics are recognised as leaders in semiconductor technology, particularly for automotive and industrial automation applications. Germany is a major global semiconductor manufacturer and the largest EU chip exporter, accounting for over a third of the total. Germany's strengths lie in the production of chips for automotive and industrial automation applications, with leading companies such as Infineon and Bosch. Germany is home to several semiconductor factories, particularly in the states of Saxony, Bavaria and Baden-Württemberg. Silicon Saxony is the largest semiconductor hub in Europe, with numerous industrial players: GlobalFoundries, Infineon Technologies, Bosch, X-FAB or SAW Components (Silicon Saxony, 2023; GTAI, 2024). For example, GlobalFoundries' Dresden factory (Fab 1) produces many different types of chips for a wide range of applications, including automotive, smartphone, 5G and IoT. It is one of the largest and most modern production facilities of its kind in Europe, a foundry that produces chips based on designs from its customers, such as Bosch, Infineon and NXP (GlobalFoundries, 2022).

In the Netherlands, NXP Semiconductors stands out, with around 11% of the global automotive semiconductor market. In 2023, it reported revenues of $13.2 billion and around 31,000 employees worldwide. In Nijmegen, it has one of the largest automotive chip factories in Europe (NL Netherlands, 2025). The Grenoble region is the main center of the French semiconductor industry, with a manufacturing ecosystem dominated by the Franco-Italian company STMicroelectronics. It produces a wide range of semiconductor devices, including microcontrollers (MCUs), RF (Radio Frequency) components, MEMS (Micro-Electro-Mechanical Systems) sensors and advanced integrated circuits for automotive and Internet of Things (IoT) applications in its factories in Crolles (northeast of Grenoble) and Rousset (STMicroelectronics, 2026). The UK has a strong expertise in compound semiconductors. South Wales is home to the world's first and only dedicated compound semiconductor cluster, known as CSconnected, which focuses on high-value manufacturing for electric vehicles, 5G, healthcare and defence (GOV.UK, 2025). Semiconductor devices are also manufactured elsewhere in Europe (Table 5, Figure 4).

Table 5. European semiconductor ecosystem – semiconductor device production.

Company	Production centers	Semiconductor devices
Infineon	Dresden, Regensburg, Warstein (Germany), Villach (Austria)	A wide range of semiconductor products, focusing on power semiconductors, analog/mixed-signal technologies, and sensors
NXP	Nijmegen (Netherlands)	Chips for the automotive sector
STMicroelectronics	Crolles, Rousset (France), Catania, Agrate Brianza (Italy)	It produces a wide range of semiconductor devices, including microcontrollers (MCUs), RF (Radio Frequency) components, MEMS (Micro-Electro-Mechanical Systems) sensors and advanced integrated circuits
X-FAB Silicon Foundries	Dresden, Erfurt, Itzehoe (Germany), Corbeil Essonnes (France)	Specialized semiconductors, focusing on MEMS and CMOS technologies, but also analog/mixed-signal integrated circuits (ICs); high-voltage chips, sensors and RF technologies

GlobalFoundries	Dresden (Germany)	Chips on 300 mm wafers
Bosh	Dresden, Reutlingen (Germany)	Advanced semiconductors, specializing in silicon carbide (SiC) power chips, MEMS and Application-Specific Integrated Circuits (ASICs)
Ams OSRAM	Regensburg (Germany), Premstätten (Austria)	Optoelectronic semiconductors (including LED chips, laser diodes and infrared components), advanced sensor technologies and analog semiconductors
SAW Components	Dresden (Germany)	Surface Acoustic Wave (SAW) devices, including filters, resonators, delay lines, and sensors for RF engineering and identification (RFID)
Semikron Danfoss	Nuremberg (Germany)	Power modules and semiconductor components
Texas Instruments	Freising (Germany)	Chips on 200 mm wafers
United Monolithic Semiconductors	Ulm (Germany)	High-performance chips
TRUMPF	Ulm (Germany)	It mainly produces photonic components and laser diodes.
Diotec Semiconductor	Heitersheim (Germany), Trbovlje (Slovenia)	A wide range of semiconductor devices (diodes, rectifier bridges)
TDK-Micronas	Freiburg (Germany)	Hall effect sensors
Nexperia	Hamburg (Germany)	Discrete semiconductors, specifically small-signal diodes, transistors, and MOSFETs
Swissbit	Berlin (Germany)	Industrial-grade flash memory products and secure storage and digital identity solutions
Smart Photonics	Eindhoven (Netherlands)	Indium phosphide (InP) based photonic chips
MACOM	Limeil-Brévannes (France)	Monolithic microwave integrated circuits and Millimeter-Wave Technologies
Vishay	Itzehoe, Heilbronn (Germany), Borgaro Torinese (Italy)	Semiconductor devices (diodes, transistors, rectifiers, power modules)
INEX Microtechnology	Newcastle-upon-Tyne (UK)	Compound semiconductors (such as GaN, SiC) and MEMS systems
Littelfuse	Chippenham (UK), Kaunas (Lithuania)	High-power semiconductors, advanced electromechanical products including sensors and switches
Pragmatic Semiconductor	Durham (UK)	Ultra-thin and flexible chips called FlexICs
Diodes Incorporated	Oldham (UK)	Advanced semiconductor components
Intel	Leixlip (Ireland)	Advanced chips
Analog Devices	Limerick (Ireland)	High-performance analog chips and MEMS systems
Hitachi Energy	Lenzburg (Switzerland), Prague (Czech Republic)	High-power semiconductors
Onsemi	Piešťany (Slovakia)	Low-voltage MOS power devices and various semiconductors for power management
Silex Microsystems	Jarfalla (Sweden)	Advanced MEMS systems
Brolis Semiconductors	Vilnius (Lithuania)	Infrared laser diodes and electro-optical systems
RD Alfa Microelectronics	Riga (Latvia)	High reliability and radiation hardened microelectronics components for aerospace and defense equipment
Mikron, Angstrem	Zelenograd (Russia)	Various semiconductor devices
Integral	Minsk (Belarus)	Chips widely used in the Russian military-industrial complex

Source: GTAI, 2024; STMicroelectronics, 2026; NL Netherlands, 2025; GlobalFoundries, 2022; GOV.UK, 2025; IDA Ireland, 2026; Hitachi Energy, 2021; onsemi, 2026; IDA Ireland, 2026; MACOM, 2026; INSIDE Magazines, 2025; Semiconductor Sweden, 2026; BROLIS, 2026; iSANS, 2025.

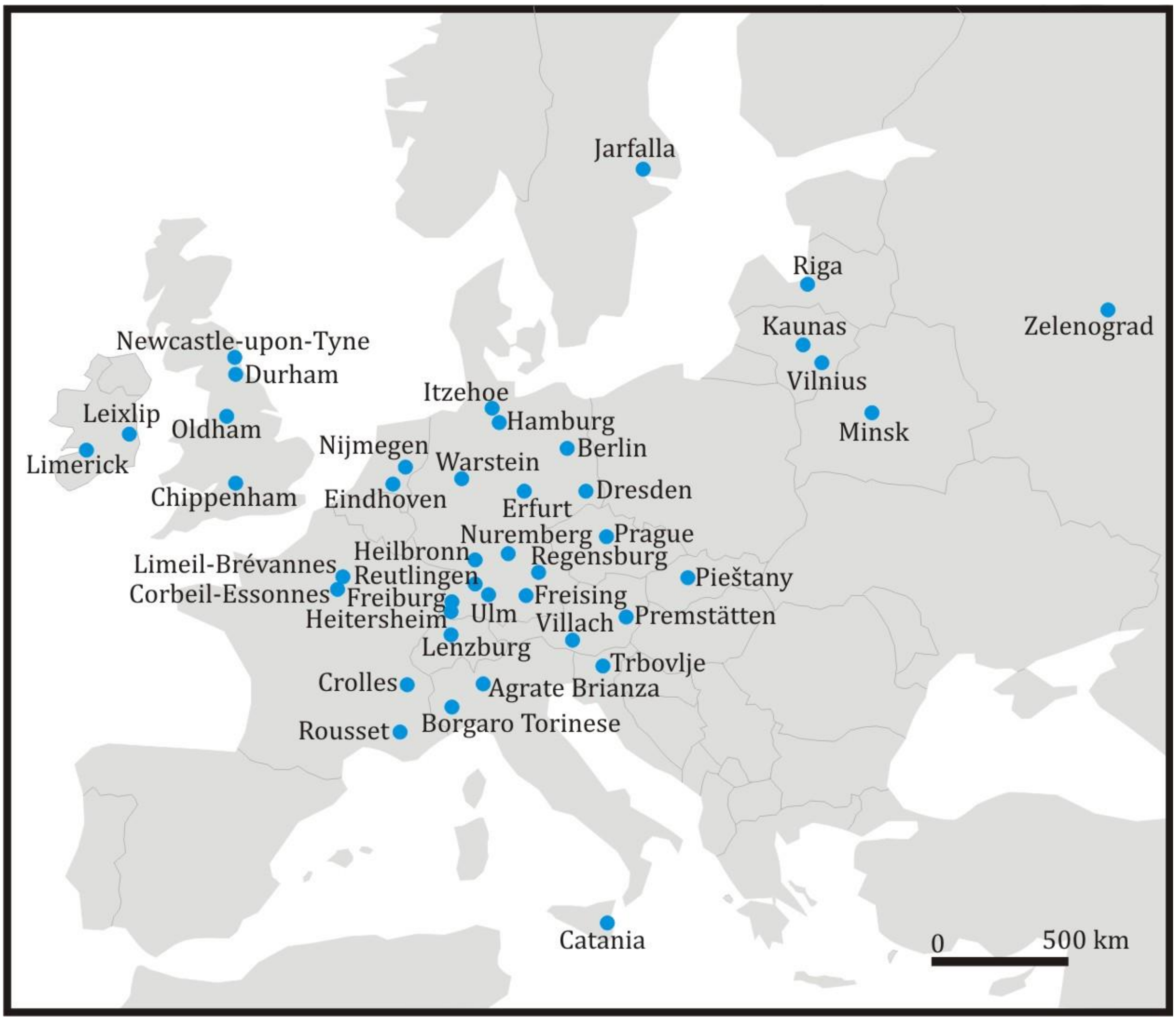

Figure 4. Semiconductor device manufacturing centers.

5. DISCUSSIONS

Global demand for electronics has grown significantly in recent years, driven by the digitalization of life and business. In 2015, global electronics sales were nearly US$2 trillion, exceeding US$2.5 trillion in 2021 and expected to reach US$3.5 trillion in 2027 (Cerutti & Nardo, 2023). In terms of semiconductors, global sales reached around US$630 billion in 2024, an increase of over 19% compared to 2023 and almost double compared to 2014 (US$336 billion). The market was dominated by the Asia-Pacific region, including Japan (US$384 billion), the Americas (US$195 billion), while Europe accounted for only US$51.2 billion. The market was dominated by sales of integrated circuits (nearly US$540 billion), mainly Logic and Memory, driven by applications related to artificial intelligence, computing infrastructure and data centers. November 2025 saw the highest monthly sales in history, with demand increasing month-on-month across all major product categories. The global chip market is expected to grow substantially in 2026 as well, reaching nearly US$1 trillion in annual sales, with growth across all regions and product categories (ESIA, 2025b; SIA, 2026).

The main problem facing Europe in this area is its dependence on external markets for the supply of various products in the semiconductor value chain, due to the complexity, geographical specialization and deep interdependencies that characterise the supply chain. In general, the United States dominates the design side, Japan the production of wafers and process gases, China the supply of key materials (gallium, tungsten, magnesium, silicon) and Taiwan and South Korea, through the foundries TSMC and Samsung, dominate chip production. TSMC is the only company that masters the most advanced nodes (2 nm), which are highly innovative and in high demand (Dauvé, 2025). Asia holds a dominant share (around

75%) of global semiconductor manufacturing capacity, with Taiwan (92%) and South Korea (8%) leading in advanced nodes (below 10 nm), while around 90% of chip assembly and testing is also concentrated in Asia, particularly in China and Taiwan (Bown & Wang, 2024; BCG-SIA, 2021; Deloitte, 2024). In terms of memory chips, which accounted for around 23% of the industry's global sales in 2022 (the most traded of all semiconductor technologies), Samsung, SK Hynix and Micron dominate almost the entire lucrative DRAM (Dynamic Random Access Memory) market (Bown & Wang, 2024).

Over the years, EU chip production has increased, but its share of global production capacity has declined significantly. In the 1990s, Europe produced over 20% of the world's chips. This decline is largely due to the rise of the fabless production model, lower manufacturing costs in Asia, and a historical focus on the needs of the automotive sector rather than on the development of high-end chips. Today, Europe accounts for around 10% of global semiconductor production (Dauvé, 2025; Meyer, 2025).

In chip production, the EU is competitive only in the DAO (discrete, analogue and optoelectronic devices) segment, with Infineon, Bosch and Osram, while for logic chips, Europe plays a minor role, with STMicroelectronics and NXP. European semiconductor companies rely heavily on suppliers and customers outside the EU. On average, in the EU supply chain, almost 80% of raw material suppliers and 63% of companies' customers are located outside the EU. Of these suppliers, the majority are based in the United States, followed by Taiwan, China, South Korea and Japan (9%) (Cerutti & Nardo, 2023). This makes the supply chain vulnerable to disruptions such as natural disasters, health crises or geopolitical tensions. Global events, such as the COVID-19 pandemic and the war in Ukraine, have exposed the weaknesses of the semiconductor supply chain and Europe's heavy dependence on foreign suppliers. About a year after the start of the COVID-19 pandemic, chip shortages have deeply affected industries around the world. In Germany, France and other countries, chip shortages have temporarily paralyzed parts of the automotive industry (Bonnet et al., 2025).

In 2013, the EU adopted a strategy to strengthen the micro- and nanoelectronics sectors (EC, 2013). Although microchip production capacity has increased substantially since 2013, it has not kept pace with global growth, so the EU's share of the global market has declined. To boost the digital transformation and Europe's sovereignty in areas such as artificial intelligence, cybersecurity and digital skills, the Digital Europe and Horizon Europe programmes (the EU's main funding programme for research and innovation) were launched in 2021 for the period 1 January 2021 to 31 December 2027 (EC, 2025a; EC, 2025b).

On 25 July 2023, the EU officially adopted a new chip law (EU Chips Act), which aims to double the EU's global semiconductor market share from 10% to at least 20% by 2030. The EU Chips Act aims to improve the EU's security of supply, resilience and technological sovereignty in chips by investing in the supply chain and by strengthening its strengths in research, design and equipment manufacturing. To support these objectives, the EU Chips Act includes public and private investments worth €43 billion, around half of which is provided by the German government (Germany Trade & Invest, 2024; ECA, 2025). Most of these funds come from industry's own resources or from Member States' budgets, with the Commission responsible for only a small part of the total, around 10% of public funding (ECA, 2025).

To boost the semiconductor sector in Europe, on 30 November 2023, the European Commission officially launched the Chips Joint Undertaking (Chips JU), a pioneering initiative dedicated to catalysing research, development and manufacturing capacities across Europe. The Chips JU programmes include the Chips for Europe initiative, which funds strategic actions such as pilot lines, design platforms and competence centres, and the ECS Research and Innovation programme, which addresses a wide range of technology areas, including artificial intelligence hardware, edge computing, cybersecurity, 6G technologies, energy efficiency, advanced packaging or photonics (CjipsJU, 2025). The Digital Europe and Horizon Europe programmes closely align with the objectives of the Chips JU, in particular through a new specific objective dedicated to semiconductor technologies.

In March 2025, nine EU Member States (Austria, Belgium, Finland, France, Germany, Italy, Poland, Spain and the Netherlands) launched the Semicon Coalition, marking an important step towards deepening cooperation in the semiconductor ecosystem in Europe, to strengthen Europe's competitiveness and strategic autonomy in the semiconductor sector by supporting research, expanding production capacity and promoting a highly skilled workforce (ESIA, 2025c).

An important step in strengthening Europe's semiconductor manufacturing capacity was the granting by the European Commission, in October 2025, of Integrated Production Facility (IPF) and Open EU Foundry (OEF) status under the EU Chips Act to four semiconductor projects across the Union. The Ams-OSRAM AG (Austria), MEGAFAB-DD of Infineon Technologies Dresden (Germany) and Catania Campus of STMicroelectronics S.r.l. (Italy) projects were granted IPF status, and the ESMC project (Germany) was granted OEF status (EC, 2025c). Both categories are essential for the EU's ambition to reduce dependence on supply chains outside the EU and increase strategic autonomy in semiconductor technologies. They will receive priority administrative support, simplified authorization processes and advanced access to pilot lines under the Chips for Europe Initiative.

Overall, the European Commission has approved state aid for several projects under the EU Chips Act until December 2025, representing a combined public and private investment of over €31.5 billion (Table 6) (EC, 2025d). These subsidies are essential for the development of the European semiconductor industry, as many steps in the production process require considerable costs. For example, building a new factory (fab or foundry) costs around $20 billion (Bown & Wang, 2024). One of the major investments is made with the involvement of Taiwan Semiconductor Manufacturing Company (TSMC), the world's largest chip manufacturer. The new company, known as the European Semiconductor Manufacturing Company (ESMC), is a joint effort between TSMC, Bosch, Infineon and NXP and aims to establish a large factory in Dresden, specializing in chips for the automotive and industrial sectors. The groundbreaking ceremony for the works took place in August 2024 (Germany Trade & Invest, 2024).

Table 6. Projects that have benefited from state aid approved by the European Commission under the EU Chip Law.

Company	Project location	Date and aid approved	Project type
STMicroelectronics	Catania (Italy)	October 5, 2022 (€292.5 million)	Construction of a silicon carbide (SiC) wafer facility using 150 mm technology
STMicroelectronics & GlobalFoundries	Crolles (France)	April 27, 2023 (€2.9 billion)	A new 300-mm FD-SOI microchips manufacturing facility
STMicroelectronics	Catania (Italy)	May 31, 2024 (€2 billion)	Building an integrated production facility for high-performance silicon carbide chips
ESMC (TSMC, Bosch, Infineon, NXP)	Dresden (Germany)	August 20, 2024 (€5 billion)	A high-performance 28/22nm and 16/12nm FinFET microchip plant
Silicon Box	Novara (Italy)	December 18, 2024 (€3.2 billion)	Advanced semiconductor packaging and testing facility
Infineon	Dresden (Germany)	February 19, 2025 (€920 million)	MEGAFAB-DD project, which can switch between discrete power and analog-mixed signal technologies
ams OSRAM	Premstätten (Austria)	February 25, 2025 (€227 million)	A CMOS - integrated production facility
Ephos	Milan (Italy)	July 25, 2025 (€41,5 million)	Development of the world's first glass-based photonic chip manufacturing plant
Onsemi	Rožnov pod Radhoštěm (Czechia)	November 20, 2025 (€450 million)	An integrated SiC manufacturing plant
GlobalFoundries	Dresden (Germany)	December 10, 2025 (€495 million)	Expanding 300mm wafer capacity for dual-use applications (aerospace and defense)
X-FAB	Erfurt (Germany)	December 10, 2025 (€128 million)	Building a new open foundry combining MEMS with innovative packaging for automotive and AI sectors (Fab4Micro)

Source: European Commission (2025d) (with additions).

Other examples demonstrate the will of European states to reduce dependence on foreign supply chains and stimulate domestic production and innovation, aligning with the EU Chips Act. Thus, the semiconductor industry in France is supported by government investment plans, such as the Electronique 2030 plan, worth around 6 billion euros. The most important investment belongs to STMicroelectronics and GlobalFoundries Fab for a jointly operated 300 mm FD-SOI microchip production facility in Crolles, which should reach full capacity by 2028 (Duncan, 2024). Also, an investment of 830 million euros, supported by the European Commission and the French state, for the FAMES pilot line, i.e. the construction of 2000 m^2 of clean rooms and the purchase of approximately one hundred new industrial equipment, was inaugurated in January 2026 in Grenoble and operated by CEA-Leti (Dauvé, 2025; EC, 2026).

In Italy, the government announced billions of euros in investments to strengthen its chip ecosystem. In 2022, it established a national chip fund (Chips Fund) for the period 2022-2030 to support R&D and industrial activities (The Italian House of Business, 2026). In the Netherlands, the government allocated 2.5 billion euros to strengthen the business climate in Brainport Eindhoven through investments in education, infrastructure and housing (NL Netherlands, 2025). Also, in 2023, the Spanish government approved the Strategic Project for the Recovery and Economic Transformation of Microelectronics and Semiconductors (PERTE Chip), with a budget of 12.2 billion euros until 2027 (financed mainly with European funds), with the aim of developing the design and production capacities of the Spanish microelectronics and semiconductor industry, covering the entire value chain (España Digital, 2023).

Despite increasing government support, in some cases very substantial, many European countries face challenges including skills shortages, intense global competition for talent or a lack of large-scale domestic manufacturing facilities. There are many views that the EU Chips Act is unlikely to be sufficient to achieve the very ambitious Digital Decade target of a 20% share of the global market value chain. This target is believed to be too ambitious, given the Commission's limited mandate and resources, the lack of coordination between countries, the reliance on Member State action, private sector investment and other factors such as energy costs (Meyer, 2025; ECA, 2025; Green, 2025).

It is estimated that Europe would need an initial investment estimated at over $300 billion to create the entire supply chain. The total development cost of a new front-edge chip (SoC) could exceed $1 billion. Additional annual costs would also be required to maintain self-sufficiency. Such additional investment would cause an increase in semiconductor prices, estimated at between 35% and 65%, which would reduce final demand and harm companies and R&D, if not supported by public subsidies (BCG-SIA, 2021).

At the same time, major players involved in the semiconductor industry (USA, China, South Korea or Taiwan) have implemented their own policies to support the semiconductor industry. In July 2022, the United States passed a historic law (CHIPS and Science Act) that provides for spending of $280 billion to stimulate scientific research and advanced semiconductor manufacturing capacity to increase US competitiveness vis-à-vis China. The bill allocated $52 billion in subsidies and tax incentives for chip manufacturing companies and $200 billion for research in artificial intelligence, quantum computing and robotics, among other areas (HAI Stanford University, 2022). In December 2022, China announced investments of approximately $143 billion over a five-year period to support domestic chip production, in response to US sanctions (Zhu, 2022). South Korea also passed legislation known as the "K-Chips Act" in March 2023, designed to boost the domestic semiconductor industry by expanding investment tax credits available to manufacturers such as Samsung and SK Hynix (Noh et al., 2023).

6. CONCLUSIONS

It is certain that human society is increasingly dependent on electronic devices, and in recent years the global demand for them has increased considerably as a result of the digitalization of life and business. In the future, this demand is expected to increase. Electronics production is heavily dependent on semiconductors, especially increasingly advanced chips, and their manufacturing is a very complex process involving hundreds of sophisticated steps and many actors.

Within the global semiconductor ecosystem, Europe stands out for its R&D capabilities, its production of chip manufacturing equipment and its highly specialized industry, such as automotive chip production. Regionally, the R&D component, including chip design, is found in almost all European countries, while the production of semiconductor equipment and devices is present in a few countries, most notably Germany.

Europe is dependent on external markets for the supply of various products in the semiconductor value chain, accounting for only 10% of global semiconductor production. The EU Chip Law aims to increase the EU's market share in semiconductors to at least 20% by 2030. Although significant funds have been allocated, achieving this target is not certain. Even so, European countries need to continue their efforts to reduce dependence on external supply chains and boost domestic production and innovation.

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The author declares they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Abiotic factors as environmental pressures on protected natural ecosystems: A case study of the South-East Region, Republic of Moldova

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ABSTRACT: Republic of Moldova is characterized by a high diversity of natural landscapes, accompanied by pronounced vulnerability to environmental change and anthropogenic pressures. This study presents an integrated assessment of geo-ecosystem vulnerability and the cumulative impact of abiotic and anthropogenic factors on natural habitat status and biodiversity conservation. It focuses on the southeastern region of the country. The research is transdisciplinary, based on the integrated analysis of geological, geomorphological, hydrological, climatic, and pedological data, correlated with the structure of the National Ecological Network and the protected natural areas system, and complemented by GIS analysis and field observations. Land use is dominated by human activities, particularly agriculture and built-up areas, at the expense of natural vegetation, which is unevenly distributed and lacks ecological connectivity. Abiotic pressures and threats include slope and soil erosion, riverbank instability, and reservoir siltation, all amplified by hydromorphological alterations of the Dniester River and its tributaries. Climate analysis reveals rising mean annual temperatures and an increasing frequency of extreme events in the region. Consequently, 70% of the study area exhibits landscape instability, with 20% of the territory categorized as highly vulnerable to climate change, which underscores the urgent need for natural heritage conservation. The overlay of the most intense environmental pressures indicates that around 18% of the study area exhibits high vulnerability, unfortunately overlapping with some of the region's most valuable protected ecosystems. To address these challenges, the study provides practical recommendations for protected area management, including enhanced ecological connectivity, habitat restoration, and the integration of climate adaptation strategies into biodiversity conservation planning.

KEYWORDS: threats and pressures, natural habitats, biodiversity, climate change, ecosystem management

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1. INTRODUCTION

The natural ecosystems of the South-East Region of the Republic of Moldova are characterized by high biodiversity and remarkable landscape complexity, determined by the region's location at the junction of two major biogeographical regions (continental and steppe) and three distinct geo-botanical districts (the Downy Oak Forest District; the Bugeac Steppe District and the South-East Region of the Moldovan Steppe District) (Postolache, 2015). This area encompasses a wide range of forest, floodplain,

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and aquatic ecosystems of significant ecological, landscape, and conservation value, as reflected by the presence of various nationally and internationally protected natural areas, including the Lower Dniester International Wetland (Ramsar Site) and the Lower Dniester National Park. At the same time, these ecosystems are increasingly exposed to both anthropogenic and natural pressures, which affect their ecological functionality and reduce their capacity to adapt to ongoing environmental changes (Tărîță, 2024).

At the European scale, biodiversity is strongly influenced by human activity, and pressures on habitats and species remain high. Intensive agriculture, urban expansion, unsustainable forestry practices, pollution, and climate change are identified as the main drivers of ecosystem degradation (IPBES, 2019).

The relevance of this study stems from the need for a comprehensive understanding of the role of abiotic factors (soil, water, air, and relief) in maintaining the biodiversity conservation status and the ecosystem services provided by protected natural areas. The aim of this research is to characterize the abiotic components of the environment and assess their current and potential impacts on biodiversity under shifting environmental and climatic conditions, in order to substantiate effective management measures.

Methodologically, the study is based on the integrated analysis of pedological, hydrological, climatic, and geomorphological data, correlated with information on the protected natural areas network, using GIS tools and field observations. The article is structured as follows: the first section presents the natural and conservation framework of the study region, followed by the research methodology; the results and discussion section examines the vulnerability of abiotic components and their implications for biodiversity, while the conclusions synthesize the main findings and provide recommendations for the adaptive management of protected areas.

The originality of the study lies in the multidisciplinary integration of environmental components and their correlation with protected-area management, while its applied value is reflected in the formulation of adaptive management recommendations and integrated conservation policies relevant for strengthening resilience and maintaining long-term ecological functionality.

2. LITERATURE REVIEW

The specialized literature highlights the decisive role of abiotic factors (climate, relief, soil, water, geographical features) in defining the habitat characteristics, control biodiversity distribution, determine the resilience of protected ecosystems to climate change and human pressure and the services that they underpin (Iordache et al., 2026; Ardeleanu, 2025; Nardone et al., 2025; Da Gama, 2023; Sumuki, 2023; Kubacka et al., 2022; Slabbert, 2021; Maebe et al., 2019, etc.).

At the global level, assessments conducted by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Bongaarts, 2019; IPBES, 2019) indicate that climate change, soil degradation, and land-use changes are major drivers of biodiversity loss. At the European level, the dominant pressures on habitats are primarily associated with intensive agriculture, land abandonment, urbanization, landscape fragmentation and climate change, processes that reduce ecological connectivity and diminish ecosystem services (EEA, 2026).

Conceptually, the classification of pressures and threats to ecosystems proposed by the International Union for Conservation of Nature provides a standardized framework for assessing the impact of natural and anthropogenic factors on protected areas (IUCN - Threats Classification Scheme, 2022). At the same time, studies dedicated to protected area management emphasize their role in biodiversity conservation and the maintenance of ecosystem services, highlighting the need to integrate physico-geographical factors into conservation planning (Dudley, 2008).

At the national level, research conducted by Postolache (2015) and Ursu (2011) underscores the relationship between natural factors and ecosystem structure, while studies on physico-geographical and climatic regionalization (Boboc, 2021; Nedealcov et al., 2013) emphasize the influence of physico-geographical conditions on the distribution and stability of ecosystems. Numerous recent studies address the particularities of individual abiotic factors, both at the scale of the entire national territory and for specific physico-geographical units, as reflected in the national atlas series. Recent investigations (Nedealcov, 2020; Atlas: Schimbările climatice și starea actuală a peisajelor, 2021; Donica et al., 2025; Cojocari & Donica, 2025) further indicate a high level of ecosystem vulnerability in the South-East Region of the Republic of Moldova, exacerbated by intensifying anthropogenic pressures and climatic aridification. Nevertheless, comprehensive assessments of territorial vulnerability to these cumulative environmental stressors, particularly those identifying dominant threats, remain notably scarce (Bunduc, 2021).

However, most studies analyze environmental components separately, without a systematic integration of abiotic factors in relation to protected areas. Research explicitly correlating physico-geographical conditions with ecosystem vulnerability within an integrated spatial analysis remains limited. In this context, the present study proposes an integrated approach that correlates abiotic factors with ecosystem vulnerability (pressure and threats) contributing to the development of adaptive conservation measures in protected areas of the South-East Region of the Republic of Moldova.

3. RESEARCH METHODS

Study area: this research focuses on the lower sector of the Dniester River, encompassing both riverbanks, and covering an area of 3,224.88 km^2. On the right bank, the administrative districts of Causeni and Stefan Voda are examined, while on the left bank the area is bounded by the Slobozia district and the administrative border between the Republic of Moldova and Ukraine. The region is characterized by considerable physical-geographical diversity and a notable concentration of protected natural areas. At the same time, it is subject to significant abiotic and anthropogenic pressures, which underlines the relevance of the study for assessing the vulnerability of geo-eco-systems.

Materials and methods: the research is based on the hypothesis that abiotic factors, together with biotic and anthropogenic drivers, represent key determinants of ecosystem vulnerability in the South-East Region of the Republic of Moldova. It is assumed that the effects of abiotic pressures and threats are intensified by extensive agricultural land use, hydromorphological alterations of the Dniester River, and the increasing impacts of climate change. Protected natural areas are considered particularly sensitive to these pressures because the conservation status of their ecosystems depends largely on the stability of the physical environment.

The methodological approach combined classical geographical analysis with Geographic Information System (GIS)-based spatial modelling to identify, classify and integrate the principal abiotic factors influencing ecosystem vulnerability. Geological, geomorphological, pedological and hydrographic maps were integrated with climatic and hydrological data, satellite imagery, Digital Elevation Model (DEM) data and field observations. Spatial analyses were performed using ArcGIS Pro and QGIS software.

The spatial database included geological, geomorphological, pedological, hydrographic and protected-area datasets obtained from national cartographic sources, together with climatic observations provided by the State Hydrometeorological Service of the Republic of Moldova. The climatic dataset consisted of multiannual records of annual and monthly air temperature and precipitation covering the period 1980–2020, corresponding to the standard climatic reference period recommended by the IPCC for climate analyses. A Digital Elevation Model with a spatial resolution of 10 m served as the basis for deriving topographic parameters, including elevation, slope gradient and slope aspect. All spatial datasets were standardized to the WGS 1984 geographic datum and projected into the UTM Zone 35N coordinate reference system to ensure spatial compatibility throughout the analysis.

Prior to spatial analysis, analogue geological, geomorphological and pedological maps were georeferenced using common control points, digitized into vector format and converted into raster datasets with a spatial resolution corresponding to the DEM. Raster datasets with different original resolutions were resampled to a common 10 m grid to ensure spatial comparability during overlay analysis. Climatic observations from meteorological stations were spatially interpolated using inverse distance weighting (IDW) interpolation to generate continuous temperature and precipitation surfaces for the study area. These raster layers were subsequently used to calculate the spatial distribution of climatic aridity.

The selected abiotic indicators included lithology, relief characteristics (elevation, slope and aspect), soil properties, hydrographic conditions and climatic aridity. Each indicator was processed individually and transformed into a standardized raster layer suitable for multicriteria analysis. Continuous variables were classified according to either internationally accepted threshold values or the statistical distribution of observations within the study area, depending on the availability of established classification schemes. Thus, the De Martonne aridity index was classified according to the thresholds proposed by Pelin (2016) and Hrnjak (2014), whereas variables lacking internationally accepted thresholds were classified using natural breaks (Jenks) to preserve the spatial variability of environmental conditions. Categorical variables, including lithological and pedological units, were grouped according to their relative susceptibility to erosion, geomorphological instability and drought.

All indicator layers were reclassified onto a three-level ordinal vulnerability scale ranging from 1 to 3, where 1 indicates low vulnerability, 2 indicates medium vulnerability, and 3 indicates high vulnerability. This scale was used only for standardizing the spatial abiotic indicators before the weighted overlay analysis. The standardized raster layers were subsequently integrated using the Weighted Overlay procedure implemented in ArcGIS. Equal weights were assigned to all abiotic indicators because the objective of the study was to evaluate their cumulative contribution to ecosystem vulnerability without prioritizing any single environmental component. The resulting raster represented the cumulative abiotic vulnerability index for the study area. The final raster was subsequently grouped into three territorial vulnerability classes: low, medium, and high. These classes are shown in Figure 11 and represent cumulative spatial vulnerability, not threat intensity.

Data interpretation focused on analysing the spatial relationships between the cumulative vulnerability index and the distribution of protected natural areas. Overlay analysis enabled the identification of sectors where multiple abiotic pressures coincide and where protected ecosystems are potentially exposed to a higher degree of environmental degradation.

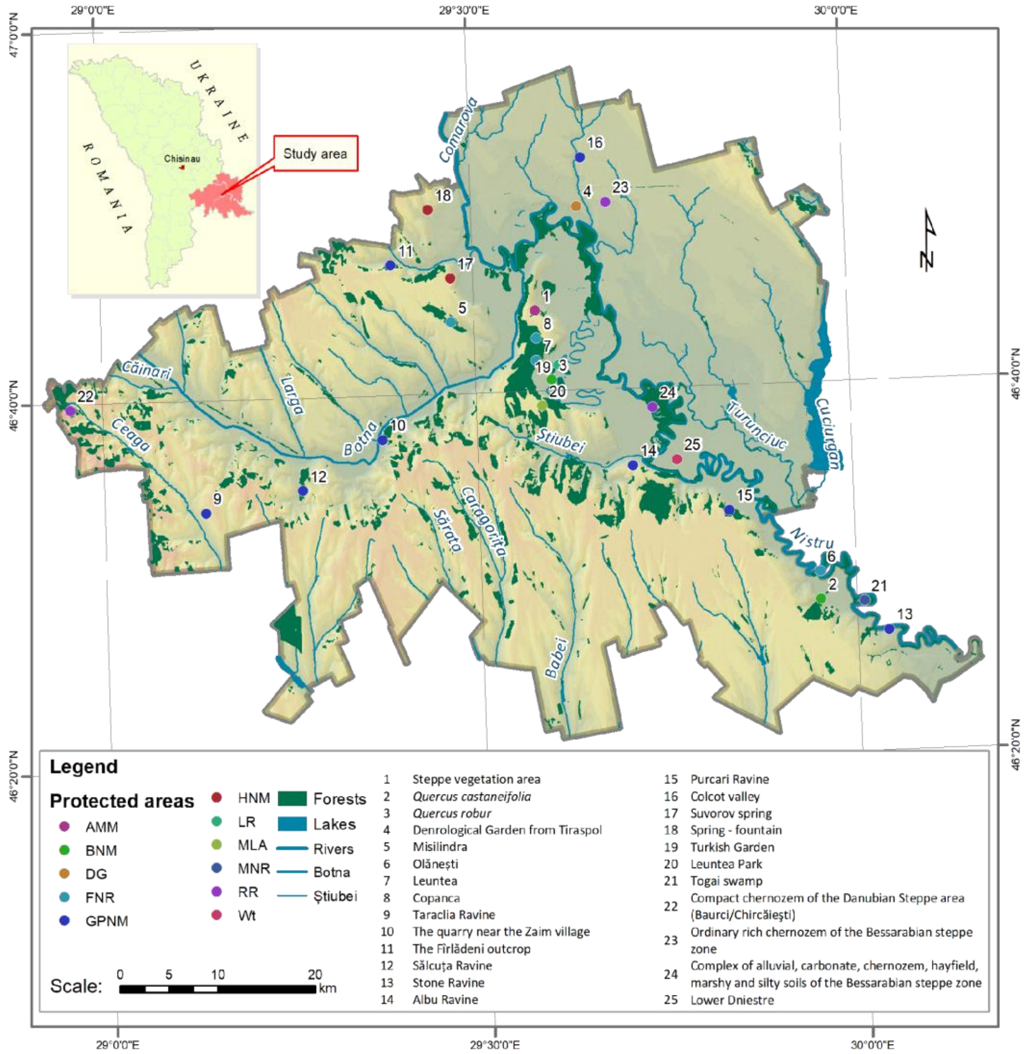
Climatic aridity was evaluated using the De Martonne aridity index (De Martonne, 1926), calculated according to the equation: $IM = P/(T + 10)$, where P represents annual precipitation (mm) and T is the annual mean air temperature (°C). The constant value of 10 was introduced to avoid negative values under low-temperature conditions. Monthly aridity was calculated using the modified equation: $IM = (12 \times P)/(T + 10)$, where P and T represent monthly precipitation and mean monthly temperature, respectively. Multiplication of monthly precipitation by 12 allows direct comparison between monthly and annual index values. According to Pelin (2016), values below 25 characterize steppe conditions, values between 25 and 30 correspond to forest-steppe environments, whereas values exceeding 30 indicate forest environments. The classification proposed by Hrnjak et al. (2014) for southeastern Europe was additionally used to evaluate the spatial variability of climatic aridity and its implications for ecosystem vulnerability.

The assessment of environmental pressures and threats was performed through thematic overlay analysis based on the standardized classification developed by the International Union for Conservation of Nature (IUCN, 2022). Particular attention was given to threat categories directly associated with abiotic processes, including natural system modifications, geological hazards, hydromorphological alterations and climate change. The spatial coincidence between these pressures and the cumulative abiotic vulnerability index allowed the identification of protected areas where natural ecosystems are most exposed to ongoing or potential environmental degradation. The resulting vulnerability patterns were finally compared with field observations collected during the survey period to verify the spatial consistency of the GIS-derived outputs.

4. RESULTS

4.1. The system of natural protected areas in the South-East Region of the Republic of Moldova

The total protected natural area in the country is 189,385.9 ha (approximately 5.61% of the country's territory). The national objective is to extend the protected area to 8% of the territory by 2030. The regulatory framework is mainly based on Low No. 1538/1998 on the fund of state-protected natural areas, with 12 categories. Seven categories are aligned with the IUCN classifications, three categories are established at the local level (Dendrological Gardens, Zoo Gardens, monuments of landscape architecture) and two categories are designed based on international instruments (Biosphere Reserve, Wetlands). The South-East Region of the Republic of Moldova, the Lower Dniester Region, is known for the variety of natural ecosystems (essential for the protection of an impressive number of rare plant and animal species), developed at the confluence of the Dniester River, strongly meandering on a low plain relief, as well as for the heterogeneity of abiotic factors in the territory (Tărîță et al., 2024). Protected-area systems, which are vital for biodiversity conservation, can help counteract environmental degradation, conserve threatened species, and protect fragile ecosystems (Dudley, 2008). In the studied territory, these areas provide essential ecosystem services, function as nature-based solutions for addressing climate change, and preserve both natural and cultural heritage. Thus, in the southeastern part of the country, natural forest, floodplain, and aquatic landscapes dominate the lower course of the river and represent outstanding natural values for the region (Figure 1). These landscapes are protected under the wetland category Lower Dniester Ramsar Site (No. 1316 on the Ramsar List of Wetlands of International Importance), covering an area of approximately 60 thousand hectares.



AMM - Areas with Multifunctional management, representative sectors with steppe vegetation	LR - Landscape Reservation
	Wt- Wetland
FNR - Forest Nature Reserve	MLA - Monument of Landscape Architecture
MNR - Mixed Nature Reserve	RR - Resource Reservation
BNM- Botanical Nature Monument, secular trees	GPNM - Geological and Paleontological Natural Monument
DG - Dendrological Garden	HNM - Hydrological Natural Monument

Figure 1. Typology and distribution of natural protected areas in the study area.
Source: Created by the authors (2026).

Forest landscapes dominated by natural fundamental stands with native species, such as pedunculate oak (*Quercus robur*), downy oak (*Quercus pubescens*), poplar, willow, and elm, together with numerous rare species of flora and fauna, are protected through Forest Natural Reserves, including "Copanca" Forest Natural Reserve, "Leuntea" Forest Natural Reserve, and "Olanesti" Forest Natural Reserve. Natural landscapes with unique geo-ecosystem values are protected through the "Grădina Turcească" Landscape Reserve (224 ha), while landscape architecture heritage is represented by "Leuntea Park" Landscape Architecture Monument (21 ha). At the same time, natural landscapes with distinctive physical-geographical values are protected through Geological and Paleontological Natural Monuments, including "Vâlceaua Colcot" Geological and Paleontological Natural Monument (16 ha), "Râpa Taraclia" Geological and Paleontological Natural Monument (12 ha), "Fârlădeni Outcrop" Geological Natural Monument (5 ha), and "Purcari Ravine" Geological Natural Monument (5 ha); as well as Resource Reserves that maintain a favorable conservation status of local natural resources, such as "Danube Steppe Compact Chernozem" Resource Reserve (Baurci/Chircaiesti, 5 ha) and "Bessarabian Steppe Typical Chernozem" Resource Reserve (2 ha). Most protected areas serve as core zones of the National Ecological Network and the pan-European Emerald Network (https://emerald.eea.europa.eu/). Furthermore, the establishment of the "Lower Dniester" National Park in 2022, covering approximately 62 thousand hectares, further highlights the ecological, aesthetic, and cultural-historical importance of the natural complexes within the lower floodplain of the Dniester River.

4.2. Physical-geographical characteristics of the study area in the formation of local natural ecosystems

Physical and geographical characteristics define an ecosystem's capacity to support life, and their alteration (through pollution, fragmentation, climate change or other human activities) leads to biodiversity loss, affecting species distribution, abundance, and adaptation. Such studies are essential for understanding how the physical-geographical structure of a territory influences ecosystem stability and their resilience to environmental changes (Gray, 2013; Barron & Gordon, 2013). For example, geodiverse areas comprise a mosaic of microclimatic refugia that are buffered from regional climate change, and therefore, these areas can provide species with a range of suitable microclimates, i.e., local climatic conditions (Määttänen, 2024).

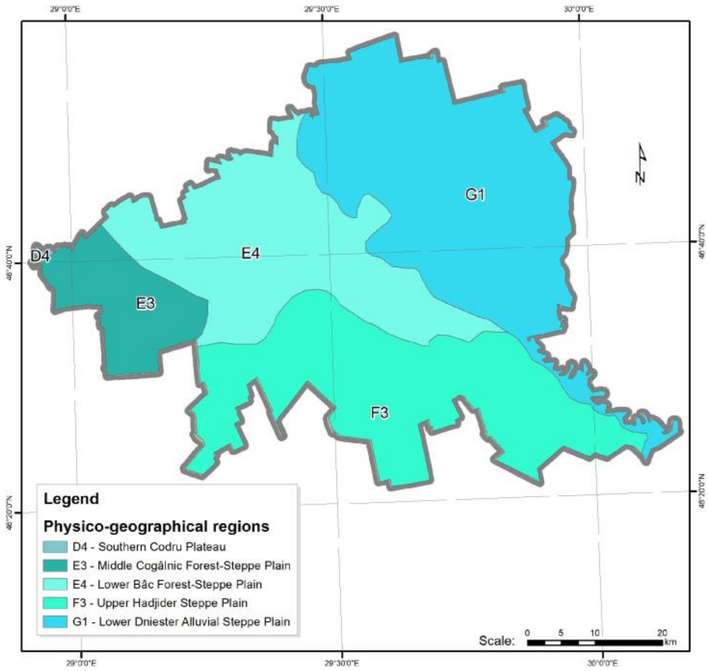


Figure 2. Physico-geographical regions.
Source: Boboc N., 2021, created by the authors (2026).

4.2.1. Physico-geographical regionalization

The South-East Region of the Republic of Moldova is part of the Southern Moldavian Plain, characterized by a gently undulating lowland relief with low altitudes and gentle slopes (Boboc, 2021).

From the perspective of physico-geographical subregionalization, the territory belongs to the following units: the Middle Cogâlnic Silvosteppe Plain (E3), the Lower Bâc Silvosteppe Plain (E4), the Upper Hadjider Steppe Plain (F3), and the Lower Dniester Alluvial Steppe Plain (G1) (Figure 2).

This arrangement gives the region *a transitional character between silvosteppe and true steppe zones*, with predominately smooth surfaces and wide interfluves, locally fragmented by valleys and alluvial floodplains, which host specific ecosystems.

4.2.2. Geological and lithological structure

The geological structure of the study region includes Neogene and Quaternary formations. The Neogene system is represented by the Bessarabian substage of the Miocene and the Akchagylian and Kimmerian stages of the Pliocene (Figure 3).

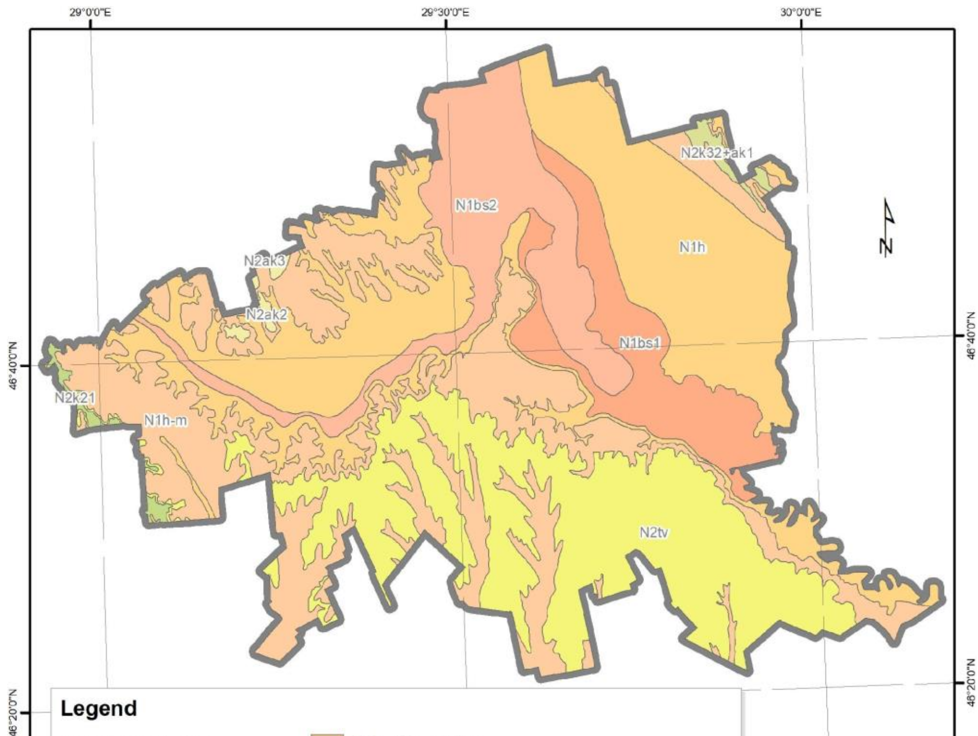


Figure 3. Distribution of geological formations.
Source: Created by the authors (2026).

The Bessarabian substage covers 2 subdivisions: 1) the lower unit (N1bs1) consists of sands, silts, clays, and reef limestones (about 8.1% of the territory), occurring mainly within the floodplain and lower terraces of the Dniester River; 2) the upper unit (N1bs2), predominantly composed of fine-grained, light gray sands, sometimes interbedded with silts, clays, and limestones, extends over more than 11.5% of the area, found in the floodplains of the Botna River and in the upper sector of the lower Dniester River. The lithological structure of these geological formations favors erosion processes and landslides, particularly during periods of heavy precipitation. As a result, geomorphological hazards pose a threat to the stability of floodplain ecosystems and to the species that depend on them.

The Khersonian (N1h) and Khersonian–Meotian (N1h–m) formations occur on and represent the most widespread geological formations in the area (approximately 29.6% of the region). They predominate in the northern sector, on the right slopes of the Botna River and the Dniester River and shaping the floodplains of several small rivers: the Ceaga River, Sarata River, Babei River, and Stiubei River. These formations play an important role in the development of agricultural lands and floodplain ecosystems. However, the respective areas are highly vulnerable to erosion and deluvial processes, especially during periods of heavy precipitation, posing a significant risk to the biodiversity.

Pontian deposits (N_2tv) cover approximately 22.7% of the region. This area represents a zone of major ecological importance, where sand and clay deposits play an essential role in soil fertility and in the formation of freshwater ecosystems. Although these deposits are relatively stable from a geological perspective, they remain vulnerable to erosion risks, particularly during prolonged drought periods, which affect both the hydrological regime of the Dniester River and the stability of floodplain ecosystems.

Deposits of the Kimmerian - the lower horizon (N_2k21) and the upper horizon (N_2k32+ak1) stage are represented by alluvium, sands, pebbles.

As geodiversity is the abiotic counterpart to biodiversity, and together these two components form the dynamics of nature that we aim to conserve, it will taken into account that Bessarabian lithological structures - the most exposed to erosion and deluvial processes- serve as geological base to the most valuable protected natural ecosystems in the region. In addition, the presence of unique and representative geological features in the region, protected through four areas, designated as Geological and Paleontological Natural Monuments, highlights the need for further studies on the territory's vulnerability to environmental changes, as well as for the development of appropriate conservation and protection measures.

4.2.3. Relief features

Altitudinal characteristics

Environmental heterogeneity dictates habitat variability and ecosystem resilience. Topographic variety, such as slopes, aspects, and elevation, creates diverse microclimates and refugia niches for different species (Berca, 2000; Keppel et al., 2012).

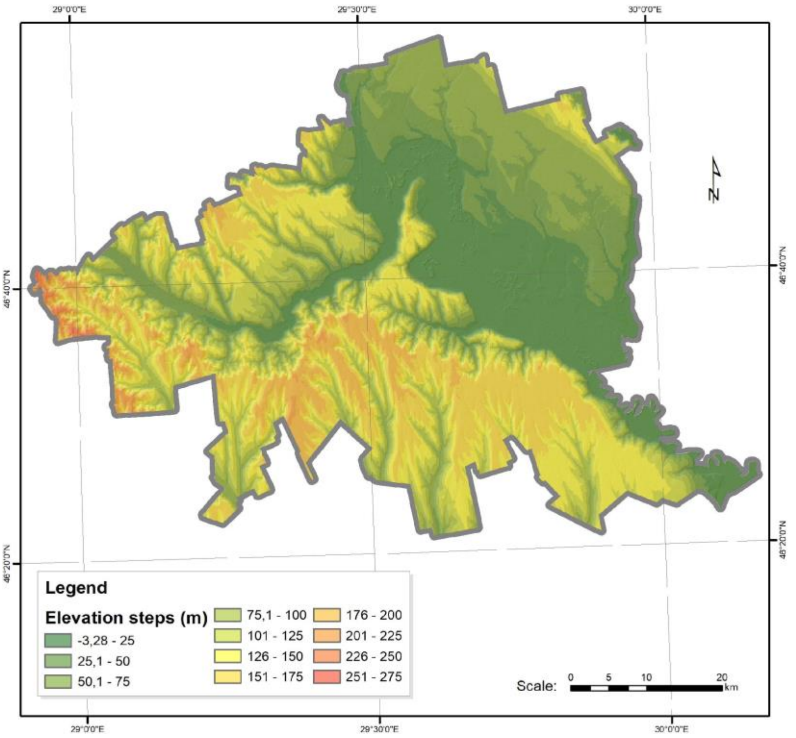


Figure 4. Hypsometric distribution of the study area.
Source: Created by the author (2026).

In the studied region, the analysis of the data indicated that the average altitude is 84.8 m and the maximum altitude reaches 257.5 m in the western extremity (Figure 4).

The percentage analysis of hypsometric levels highlights a pronounced altimetric asymmetry, determined by the high proportion of surfaces located below 100 m altitude. More than 55% of the region's surface corresponds to the floodplains and lower valleys of the Dniester River and its tributaries. The lowest elevations are found in the Dniester River floodplain (an area known as the region with the lowest altitudes in the country, with negative elevations). A relatively high proportion, exceeding 44%, corresponds to the hypsometric level between 100 m and 200 m.

Slope

The analysis of relief characteristics represents an essential tool for identifying areas susceptible to active geomorphological processes (such as erosion and landslides), correlating altitudinal distribution with landscape types, and assessing the ecological stability of landscapes, with direct implications for biodiversity. Slope represents a fundamental morphometric parameter of relief, as it reflects the geological structure, the geomorphological evolution stage, and the types of both present and past land-shaping processes (Patriche, 2005). Slope controls processes such as water erosion and landslides, influences the solar radiation regime, soil formation and continuity, vegetation distribution, and patterns of land use (Bănică, 2006). In this study, slope gradient values were classified into five categories (classes) based on morpho-dynamic criteria adapted to local and regional conditions, in order to highlight areas with high susceptibility to environmental degradation processes (Figure 5).

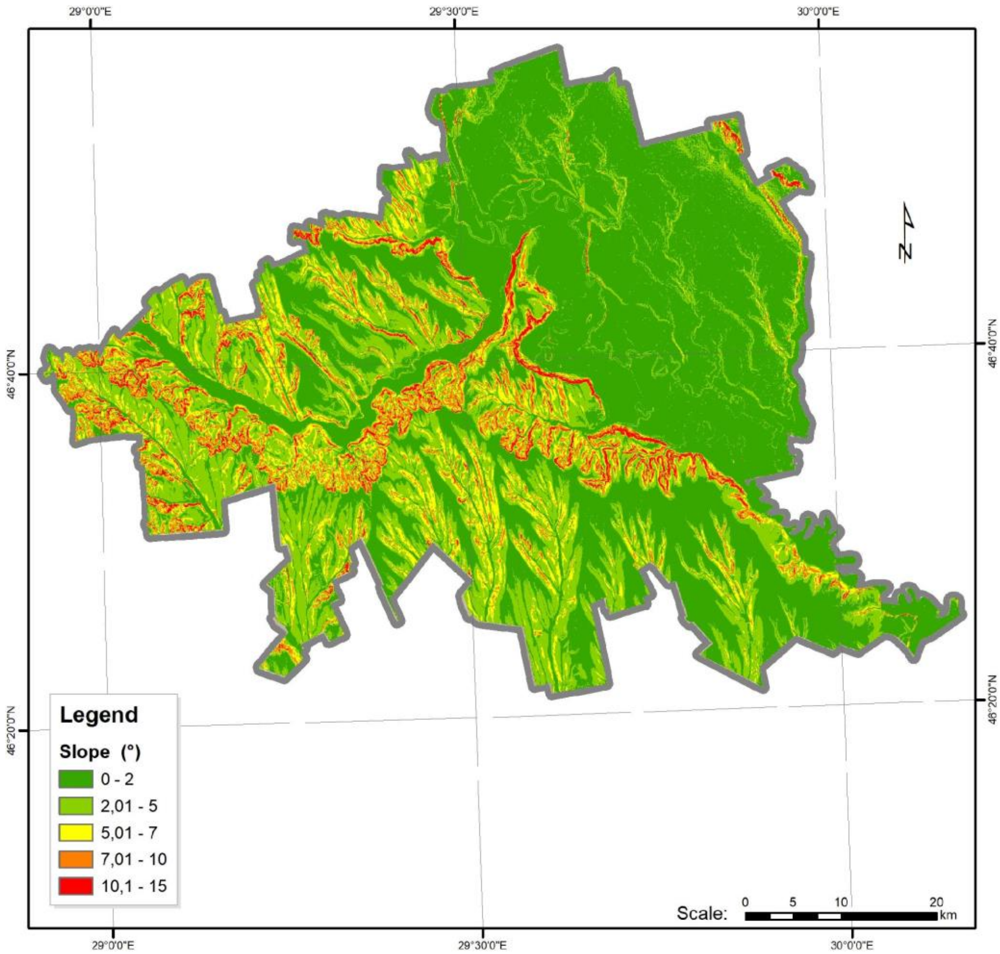


Figure 5. Slope on the terrain.
Source: Created by the authors (2026).

The analysis of slope gradients in the South-East Region of the Republic of Moldova-highlights the predominance of gentle slopes, under 2°, which cover more than 54% of the total area. These surfaces are primarily located in the floodplains of rivers traversing the region, as well as in the upper parts of slopes, at the interface with interfluve ridges. Slopes ranging from 2–5° also occupy a significant proportion, approximately 28%, while slopes of 5–7° account for just over 9% of the total area.

Slopes within the 7–10° range cover about 6.33% of the territory and generally correspond to moderately inclined surfaces, including river terraces, transition zones between floodplain and slope, gently inclined slopes, and the junctions between interfluve ridges and slopes. Slopes of 10–15° make up approximately 2.27% of the total area and mark the threshold at which linear erosion processes become active, favoring the development of rill networks, gullies, and ravines. Slopes greater than 15° are virtually absent in the study area. Areas with gentle slopes, coinciding with floodplains and river terraces, encompass the most important floodplain ecosystems and protected wetlands, but they are also exposed to erosion and instability under intense precipitation events, representing sensitive zones susceptible to environmental pressures and threats.

The distribution of slopes by aspect (the angle between the north direction and the slope direction, measured clockwise) in the South-East Region of the Republic of Moldova is heterogeneous, resulting in a mosaic of relatively small surface units (Budui, 2002). The largest proportions are recorded for east-facing slopes (17.8%), characterized by cooler and semi-shaded conditions, followed by southwest-facing slopes (16.8%), west-facing slopes (14.2%), and south- and southeast-facing slopes (both 11%). The smallest proportions occur on northwest-facing slopes (6%) and north-facing slopes (7%). Overall, the cumulative share of sunny and semi-sunny slopes (53.7%) is comparable to that of shaded and semi-shaded slopes (46.3%), indicating a relatively balanced distribution of microclimatic conditions at the regional level. This aspect structure locally controls moisture availability, soil stability, and vegetation distribution, thereby directly influencing the sensitivity of protected natural ecosystems to climatic and anthropogenic pressures (Patriche, 2005).

Thus, the relief characteristics and local microclimate have created favorable conditions for the development of natural vegetation communities: floodplain vegetation on Dniester meadows, steppe vegetation and thermophilous sub-Mediterranean forests on fields (Postolache, 2015).

Soil cover

The diversity of natural pedogenetic factors in the South-East Region of the Republic of Moldova, particularly lithological conditions, climatic regime, and relief morphology, has led to the development of a complex and varied soil cover (Figure 6).

Against the general backdrop of steppe and forest-steppe landscapes, characteristic of the south east of the country, automorphic soils of the chernozem class predominate, complemented by hydromorphic and halomorphic soils, which are distributed in an insular pattern within depression and floodplain areas.

Automorphic soils constitute the dominant pedogenetic background of the region, covering well over half of the total area (approximately 70%) and developing extensively on loess and loessoid-deluvial deposits under conditions of favorable natural drainage and a relatively balanced hydric regime. Within this group, chernozems occupy a central position: the carbonate chernozem is the most widespread in the southern and southeastern parts; leached chernozem occurs on interfluve plateaus and gently sloping hillsides; typical chernozem is distributed across the central and northern areas; and vertic chernozem appears sporadically in low-lying depressions. Overall, the chernozems of south-eastern Moldova are almost entirely integrated into the agricultural cycle, used for arable fields, vineyards, and orchards. Intensive exploitation has locally led to the degradation of soil aggregate structure and a reduction in organic matter content, particularly on lands exposed to erosion and deep plowing (Ursu, 2011).

However, there are also small protected areas of chernozems - Resource Reserves (RR), within the study area (RR “Compact Chernozem of the Danube Steppe region”, covering 5 ha; and RR “Typical Fat Chernozem of the Bessarabian Steppe region”, covering 2 ha), which underscores the importance of studying factors affecting protected areas.

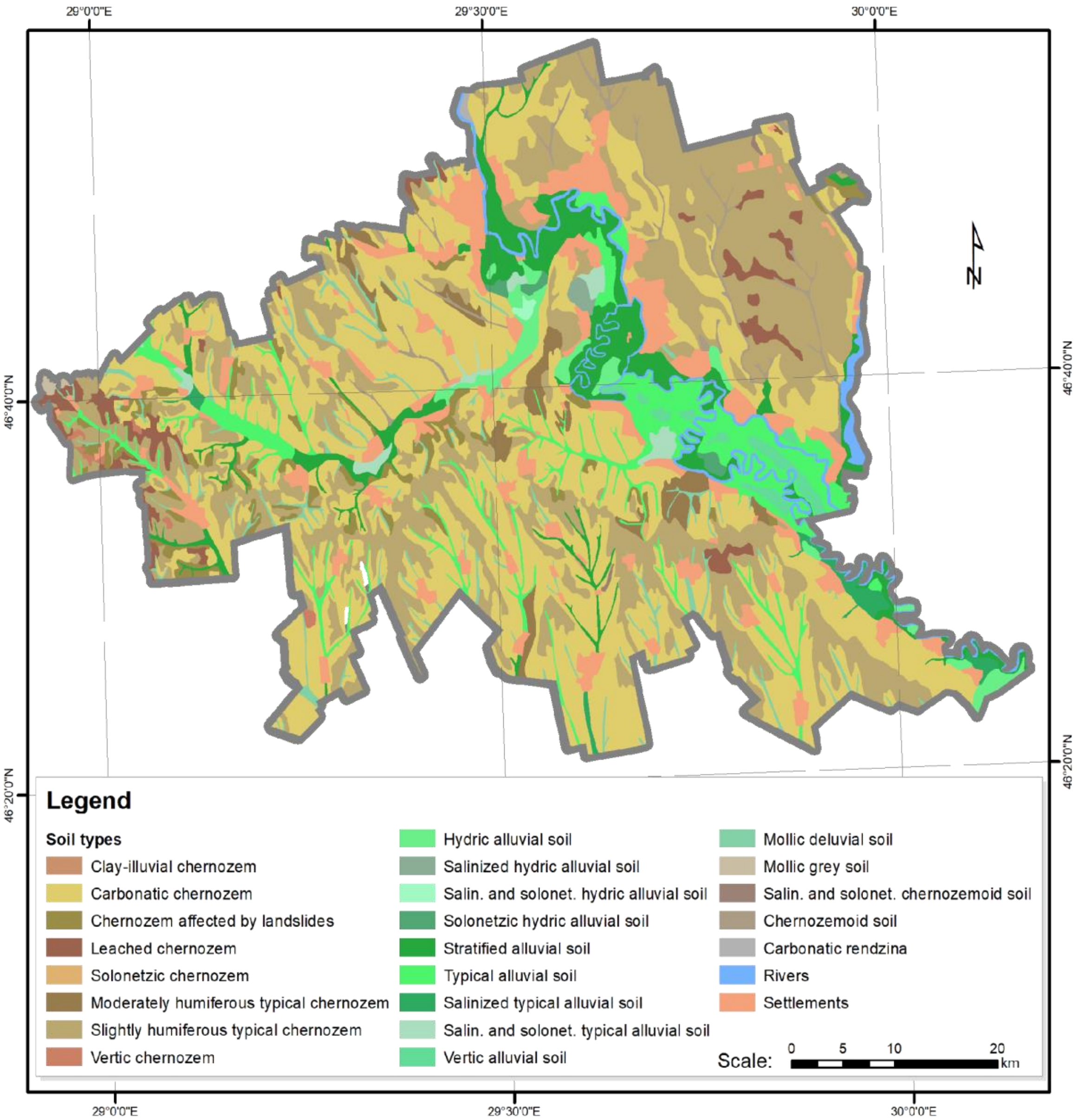


Figure 6. Spatial distribution of soil subtypes.
Source: Created by the authors (2026).

Hydromorphic soils have a limited distribution, developing primarily in the floodplain of the Dniester River and smaller tributaries, in local depressions where water temporarily accumulates, the groundwater table is high, and natural drainage is insufficient. In the transition zones between slopes and floodplains, deluvial soils have developed through the accumulation of eroded material. The alluvial soils of the Dniester and its tributaries are distinguished by clear stratification and high natural fertility and are frequently used for vegetable and fodder crops where the risk of flooding is controlled (Ursu, 2011).

In the South-East Region of the Republic of Moldova, the more arid climate, combined with slope, soil texture, and human pressures (deforestation, deep plowing, monocultures), exacerbates the phenomenon of land degradation (IPBES, 2019).

For the study area, the degradation pattern indicates a predominantly stable pedological background: 48% of the soils are uneroded, complemented by the floodplains (21%) – areas that are relatively little affected by erosion but subject to hydromorphic risks. Nevertheless, erosion impacts approximately 20% of the territory (12% slight, 6% moderate, 2% severe), while landslides cover 11%, with localized high impacts on the slopes (Figure 7). Slopes affected by erosion, however, provide favorable conditions for steppe vegetation, which has established herbaceous plant communities due to the local topo-climatic conditions and the fact that these slopes are excluded from agricultural use.

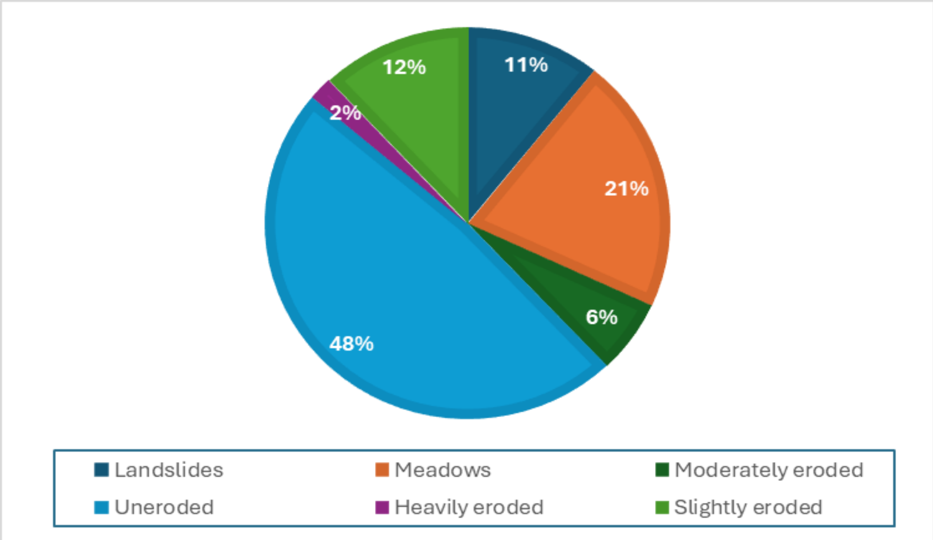


Figure 7. Soil erosion categories.

Hydrographic network

The Dniester River is the most important water source in the region. The average multiannual water volume of the Dniester River is about 9.2 km^3, varying between 6 km^3 in dry years with a moisture deficit and 12 km^3, values reached in years rich in water resources. The multiannual average of the flow at the Bender hydrological station (the closest to the study region) in the years 1980-2022 was 272 m^3/s, which falls within the limits of 4.68-6.49 l/s, and the runoff layer amounted to values of 148-205 mm. In the last 10 years, however, a decrease in the average flow by 17 m^3/s has been recorded, which can be explained by the consequences of climate change and damming of riverbeds. It is likely that the decrease in runoff in recent years is part of a new cycle of low water levels, which began in 2011.

The main supply sources for the river are snow and rain, with groundwater playing a much smaller role. Most precipitation falls as rain showers and only 10% falls as snow. A high water level is recorded in spring due to snowmelt (40-50% of the annual runoff). In the summer season, with the torrential rains, the levels of rivers, especially small ones, can rise considerably, sometimes causing major floods. (Dniester River Basin Management Plan, 2025).

The hydrographic network in the studied region has a total length of approximately 869.4 km, comprising a complex system of interconnected watercourses and river segments. Due to its geographical location, morphometric and hydrological characteristics, the region's hydrographic network is part of the Dniester and Black Sea drainage basins. Thus, the network encompasses the lower segment of the Dniester River, along with the Colcotov–Cuciurgan and Iagorlîcul Uscat–Comarova sub-basins located on the left bank of the Dniester, as well as the Nistrul Vechi–Stiubei–Liman and Botna sub-basins on the right bank. At the same time, the network includes several secondary rivers - Caplani, Babei, Caragorita, Sarata, and Ceaga - which are part of the Prut–Danube–Black Sea hydrological district (Figure 8).

According to data (The National Geospatial Data Fund of the Republic of Moldova), approximately 89 water reservoirs have been identified in the South-East Region of the country. In terms of origin, all these reservoirs are anthropogenic, created either by damming watercourses or by establishing artificial basins. Among them, the largest is the Cuciurgan reservoir, with a surface area of approximately 25.01 km^2, followed by the Crasnoe reservoir, covering around 2.4 km^2. The remaining reservoirs are smaller than 1 km^2, with the smallest measuring only 0.0026 km^2. In total, the water surface area of all reservoirs in the region amounts to approximately 40.4 km^2, highlighting a significant density of artificial water bodies within the regional hydrographic network.

Thus, in the region, the natural ecosystems functioning, the natural habitats maintenance and biodiversity conservation, mainly specific to wetlands and bird areas are directly formed and supported by the supply of the Dniester River with water and nutrients.

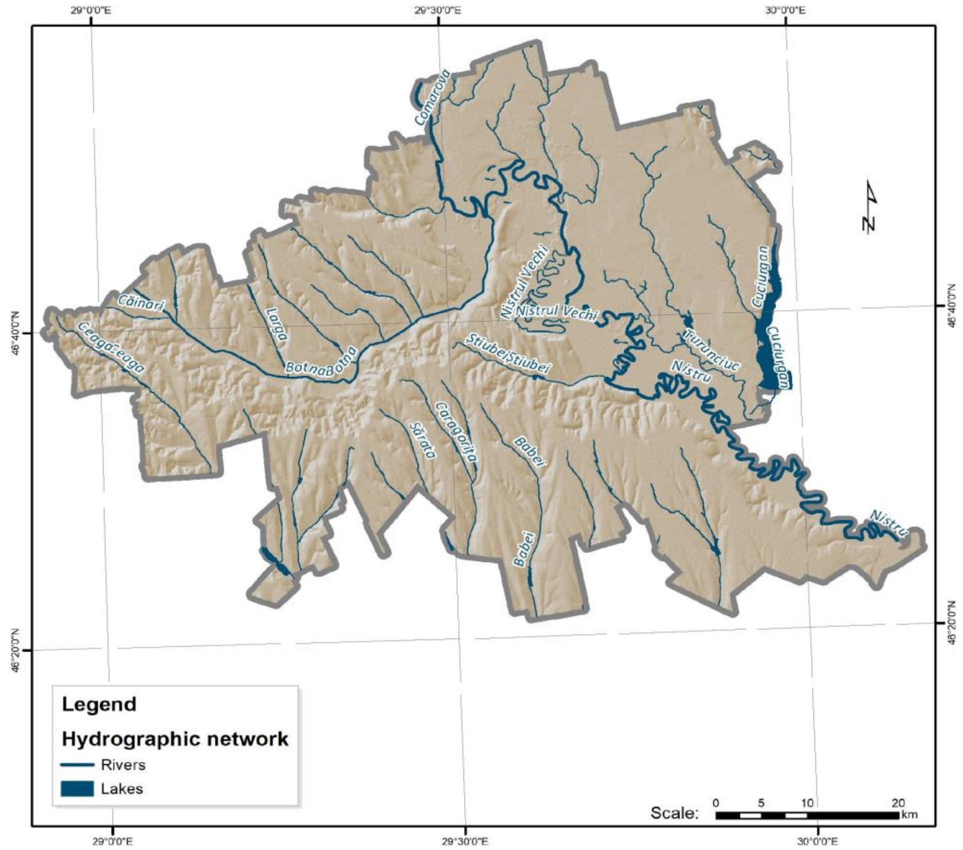


Figure 8. Hydrographic network.
Source: Created by the authors (2026).

Climatic characteristics

From the perspective of climatic regionalization, the territory of the Republic of Moldova is situated within a temperate continental climate zone. In the southern part of the country, this climate is further influenced by the proximity of the Black Sea, as well as by the air masses advection, originating from the Mediterranean region. The specific features of the general atmospheric circulation in the central and south-eastern part of Europe, together with the "openness" of the territory towards the Black Sea, represent the main factors that induce noticeable local variations in atmospheric dynamics, with direct effects on the thermal regime and precipitation patterns (Nedealcov, 2013).

The relief fragmentation degree exerts a direct influence on the spatial distribution of the thermal regime, through the effects induced by altitude and slope aspect. An analysis of data from the scientific literature indicates that the multi-annual average temperatures (1991–2020) recorded in the South-East Region of the Republic of Moldova (10.0–11.9°C) exceed, in quantitative terms, the national multi-annual average (10.8°C). In temporal terms, the coldest month of the year – January - records average temperatures of −1.8°C in the study area, which is 0.5°C higher than the national average (−2.3°C) (Atlas Republica Moldova: Factorii naturali și antropici de risc, 2020). For the warmest month – July - a similar difference is observed between the national average (21.8°C) and the values recorded in the southeastern part of the country (23.1°C), indicating a thermal surplus (Atlas: Factorii abiotici de mediu și securitatea ecologică, 2023).

The absolute annual maximum air temperature (1991–2020) indicates average peak values of 36.0°C in the South-East Region of the Republic of Moldova, compared to the national average of 35.1°C. From a temporal perspective, this parameter, recorded at the Stefan Voda Meteorological Station, shows high values, ranging from 31.7°C (in 2004) to an absolute maximum of +41.1°C recorded in 2007. The upward linear trend (+1.8°C per decade) reflects the general tendency toward increasing aridity in the region.

The absolute annual minimum air temperature (1991–2020) indicates, for the South-East Region of the Republic of Moldova, minimum values of −18.2°C, compared to the national average of −18.5°C. From a temporal perspective, this parameter, recorded at the Stefan Voda Meteorological Station, shows low values ranging from −25.3°C (in 2006) to −8.3°C (in 2020). The slightly increasing linear trend (+0.6°C per decade), although barely perceptible, aligns with the general trend of increasing aridity and ongoing climate change in the region (Cojocari, 2025).

For the study region, the average annual precipitation amounts to approximately 510 mm, which is about 30 mm lower than the national average of the Republic of Moldova. Recent climatic studies project significant changes in both the mean annual temperature and the average annual precipitation for the tree vegetation period (April - October) in the South-East Region of the country, with a particular emphasis on the summer months (June - August), which are characterized by high air temperatures and low precipitation input (Raileanu, 2021).

Land use structure

The land use structure in the South-East Region of the Republic of Moldova reveals a clearly dominant agricultural profile, reflecting the region's traditional economic orientation and the high degree of its soil resources utilization. The total analyzed area exhibits a differentiated distribution among agricultural lands, forested areas, pastures, wetlands, water bodies, and built-up areas (Figure 9).

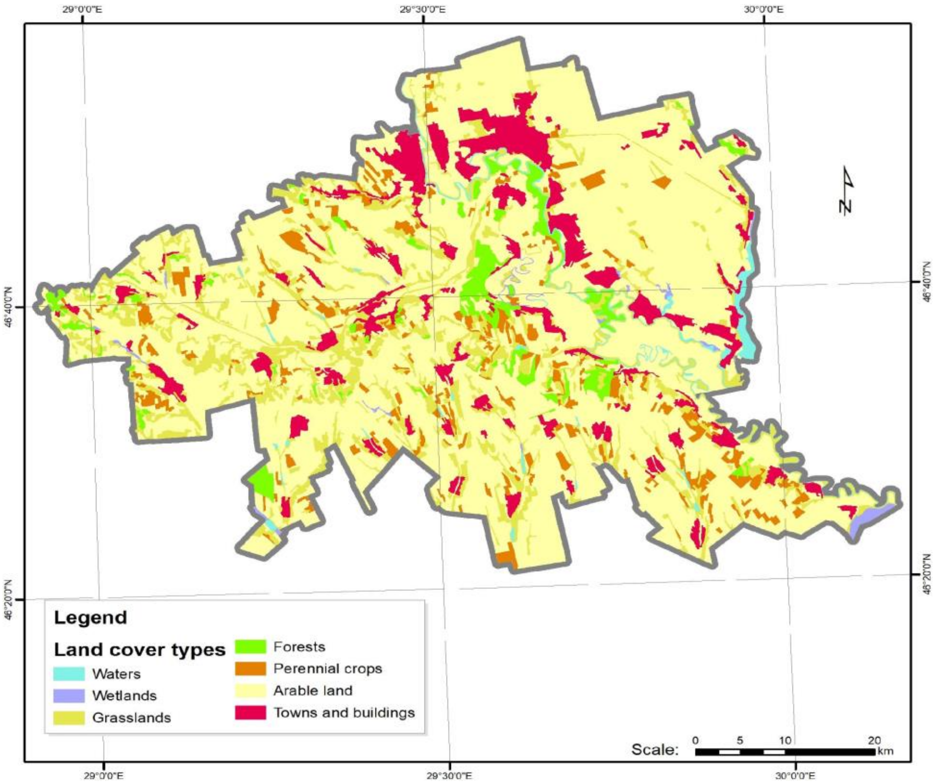


Figure 9. Land use categories.
Source: Created by the authors (2026), Corine Land Cover, 2023.

According to cartographic and statistical data, arable land represents the principal component of the functional structure, covering 216,142 hectares, which accounts for approximately 67.5% of the total area. This highlights a pronounced agricultural specialization, primarily focused on the cultivation of cereals and industrial crops, supported by the high fertility of chernozem soils, to the detriment of sectors with natural vegetation, which are unevenly distributed.

Pastures occupy a significant share, amounting to 41,952.5 hectares (13.1%), and are primarily distributed on hilly slopes and in areas characterized by vertic or partially hydromorphic soils. In addition to their importance for grazing, these lands also fulfill an essential ecological role, acting as buffer zones against erosion, landslides, and soil loss.

Perennial crops, particularly vineyards and orchards, cover 17,519.3 hectares (5.5%) and are distributed in a mosaic pattern across the region, where topoclimatic conditions are favorable for perennial species.

The forest fund, although more limited in extent compared to other regions, covers 11,142.7 hectares (3.5%) and represents an essential component for the ecological stability of the landscape. Forests are distributed in a fragmented manner, particularly on slopes prone to erosion and in the vicinity of watercourses, contributing to the regulation of the hydrological regime and air temperature.

Settlements and built-up areas total 29,150.3 hectares (9.1%), being concentrated around administrative centers and along major transport corridors (Chisinau - Causeni - Stefan Voda - Palanca). Their expansion reflects a process of gradual urbanization, still below the national average in terms of density.

Water surfaces, totaling 4,740.45 hectares (1.5%) - including the Dniester River and reservoirs - play a crucial role in regulating the hydrological regime and maintaining biodiversity. At the same time, wetlands, covering 1,703.63 hectares (0.5%), are associated with floodplains and low-lying depressions, where water stagnation and hydric soils frequently occur.

5. DISCUSSION

Threats represent one of the most important concepts in conservation practice. Direct threats include current or future human activities that are the immediate cause of ecosystem degradation and loss, or of species population decline. They also encompass major stressors within natural systems whose dynamics have been altered by the effects of present or historical human actions (IUCN Red List of Threatened Species, 2022).

Direct threats constitute the critical interface through which human socio-economic systems impact and modify natural systems and are, therefore, the direct or indirect target of many conservation actions. It is important to note that the IUCN classification lists only human activities and stressors that may pose threats to conservation targets; it does not describe the actors or the targets themselves. Furthermore, this classification does not explicitly aim to include methods for assessing the magnitude (scope and severity) of a given threat.

The analysis of threats affecting protected areas in the South-East Region of the Republic of Moldova identified climate change as one of the most significant threats within the category of abiotic factors, followed by the category of Natural System Management and Modifications.

5.1. Climate change

The vulnerability of protected ecosystems to climate change can be quantified through the calculation and interpretation of eco-climatic indices (Hrnjak, 2014). Recent studies on the territorial aridity degree, expressed by the De Martonne Aridity Index (IM), indicate that the southeastern part of the country is predominantly classified within semi-humid conditions (approximately 60% of the territory), with IM values 24.0-28.0 units, followed by Mediterranean-type conditions (IM values between 21.8–24.0 units), covering about 40% of the studied area (Cojocari, & Donica, 2025).

The suitability for the development of specific vegetation formations, depending on IM values, places the study area within two distinct subtypes: (a) IM values between 20–25 units, indicating conditions favorable for the development of tall-grass steppe, and (b) IM values between 25–30 units, indicating conditions favorable for forest-steppe/silvosteppe development. Consequently, protected forest ecosystems in the region are of increased importance for maintaining ecological stability.

A comparison between the multiannual IM values (1980–2020) and literature data on forest vulnerability to aridity indicates that forest ecosystems in the South-East Region fall into two vulnerability zones: (a) a zone of very high vulnerability (IM values below 25 units), covering approximately 20% of the study area, and (b) a zone of high vulnerability (IM values between 25–30 units), covering about 80% of the territory. Notably, most protected forest ecosystems in the region, such as FNR Copanca, FNR Leuntea, FNR Olanesti, the eastern sector of the “Lower Dniester” National Park, among others - are located within the very high vulnerability zone (Donica, 2025).

5.2. Natural System Management & Modifications

A) Fire & Fire Management

The most exposed to this threat are forest ecosystems, predominantly found within the region's forest nature reserves, as well as vegetation in protected steppe sectors.

B) Dams & Water Management / Use.

Human activities alter or fragment aquatic habitats, modify water discharge and chemical composition, and/or lead to water scarcity or excess within ecosystems. Hydromorphological changes of the Dniester River and its tributaries are caused by the construction of dams and reservoirs along watercourses, which disrupt the longitudinal connectivity of rivers, as well as by flood protection dikes and irrigation channels that affect the lateral connectivity between the river and its floodplain. In the floodplain of the Dniester River, protective dikes are constructed in the lower course, at a distance of 20–100 m from the minor riverbed, with heights reaching up to 4 m (GD. No. 814, 2017).

Other relevant pressure categories identified under the IUCN classification include:

5.3. Use of lands and waters

A) Residential, Commercial & Recreation Areas (urban areas, suburbs, villages, rural housing etc.).

Settlements and constructions in the region have a more pronounced impact on natural ecosystems located in the northeastern part of the studied area and along the valleys of local rivers, through conversion and degradation effects caused by their expansion and continuous presence. In the case of the consolidation and expansion of the human settlement system, particularly near the Dniester River, where most of the forest nature reserves are located, including the Lower Dniester Ramsar Site and the Lower Dniester National Park, a moderate threat to the natural ecosystems of the region is anticipated.

B) Agriculture & Aquaculture.

In the studied region, agricultural activities are dominant, reflecting the traditional economic profile of the area and the high level of utilization of soil resources. Intensive agricultural specialization, focused on cereal and industrial crop cultivation, leaves little room for natural vegetation. Agriculture and livestock farming, including expansion, intensification, or the agricultural practices employed, can impact the environment and also leave a spatial footprint through the facilities required for these activities.

(a) **(b)**

Figure 10. (**a**) Old branch of the Dniester River, drying up due to the aridification of the climate; (**b**) Landslides, on the right slope of the Dniester River, stabilized by vegetation and agricultural lands on river meadow.
Source: Donica A., 2025.

A study on the ecological stability of landscapes (by K ecological stability coefficient) in the South-East Region of the Republic of Moldova indicates that unstable landscapes cover approximately 70% of the study area, while stable landscapes account for only 30% of the territory (Angheluta, 2025). This spatial distribution highlights significant degradation of natural landscapes despite existing conservation efforts, primarily due to ongoing human pressures such as unsustainable management of forests, grasslands, and meadows, agricultural expansion, environmental pollution, land degradation, climate change, and low connectivity among elements of the National Ecological Network (Donica, 2025) - (Figure 10).

5.4. Transportation, Service & Security Corridors

Transport corridors in the region (R28, R30, R52) exert specific pressures on biodiversity through habitat loss and fragmentation, including effects associated with their use (e.g., vehicle-caused mortality, restriction of species movement).

5.5. Natural Disasters

Geological Events

Landslides affect 10.7% of the studied territory, impacting the ecological stability of natural habitats located on slopes.

As a preventive analysis, we indicate that environmental pressures, such as climate change and the forecasted trend of climate aridification, land use patterns, and exogenous processes induced by this pressure, the dynamics of river waters and hydromorphological changes are considered abiotic factors with an obvious negative impact on the natural heritage in the southeast of the country (Table 1).

Table 1. Author-derived estimates of the intensity of some current/ongoing threats to protected ecosystems in the South-East Region of the Republic of Moldova.

IUCN Threats Class (version 4.0)		**Author-derived threat intensity score, 0 - 4**	**Evidential basis for intensity score**
IUCN-CMP threat category	**IUCN-CMP threat subcategory**		
A. Use of Lands & Waters			
1. Residential, Commercial & Recreation Areas	Residential Areas (urban areas, suburbs, villages, rural housing, vacation homes, shopping areas, offices, schools, hospitals, etc.)	1	Localized expansion of settlements and rural housing in the vicinity of protected ecosystems; limited direct spatial overlap.
	Commercial & Industrial Areas (stand-alone office parks, stand-alone shopping centers, manufacturing plants, sewage treatment plants, landfills, etc.)	1	Existing commercial and industrial facilities occur locally; their influence on protected ecosystems is spatially limited.
	Recreation & Tourism Areas (visitor facilities in parks, campgrounds, football or other sports fields, cultural tourist attractions, cemeteries etc.)	1	Recreational and tourism activities occur at selected protected sites, with localized visitor-related pressure.
2. Agriculture & Aquaculture	Annual & Perennial Non-Timber Crops (farms, household swidden plots, orchards, vineyards, mixed agroforestry systems, biofuel crops, haying practices that disturb nesting birds etc.)	2	Extensive agricultural land use surrounding protected ecosystems and direct/indirect pressures associated with cultivation, including habitat fragmentation, agrochemical inputs and land-use conversion.
	Wood Plantations (acacia plantations, pulp or fiber plantations, firewood lots, etc.)	1	Plantation areas occur locally and have a limited spatial extent compared with natural and semi-natural ecosystems.

	Terrestrial Animal Farming, Ranching & Herding (cattle feed lots, dairy farms, cattle ranching, chicken farms, goat, bee keeping, etc.)	1	Livestock farming and grazing occur in the region, but their documented impact on protected ecosystems is predominantly localized.
3. Transportation, Service & Security Corridors	Roads, Trails & Railroads (highways, secondary roads, logging roads, biking trails, bridges & causeways, public transport systems, railroads, etc.)	0	No significant current evidence of a direct and substantial threat to protected ecosystems at the regional scale; impacts are mainly localized.
	Utility & Service Lines (electrical & phone wires, aqueducts, powerlines etc.)	0	Existing infrastructure is spatially limited and no significant current impact on protected ecosystems was identified at the regional scale.
B. Use / Management of Species & Ecosystems			
1. Natural System Management & Modifications	Fire & Fire Management (fire suppression to protect homes, inappropriate fire management, building of fire breaks, escaped agricultural fires, arson, campfires, etc.)	1	Agricultural and accidental fires occur periodically in the region and may cause localized disturbance to natural and semi-natural habitats.
	Dams & Water Management / Use (dam operations, levees and dikes, channelization, highway culverts, water catchment areas, snow fences, surface water withdrawals, groundwater pumping, artificial lakes, water treatment plants, etc.)	1-2	Water abstraction, hydraulic infrastructure and hydrological regulation affect water availability and flow regimes; intensity varies among locations and ecosystems.
2. Natural Disasters	Geological Events (earthquakes, landslides, etc.)	1	Landslides and other geological processes occur locally and may affect individual protected sites, but their regional impact is limited.
	Severe Weather Events (rain/wind storms, hail storms, blizzards, dust storms, floods, etc.)	1	Floods, storms, hail and other extreme events occur periodically and may cause localized ecosystem disturbance.
3. Climate Change	Changes in Temperature Regime (heat waves, cold spells, etc.)	2	Increasing temperatures and recurrent heat extremes represent a regional-scale pressure with implications for ecosystem functioning and species vulnerability.
	Changes in Precipitation & Hydrological Regimes (rainfall patterns, droughts, timing of rains, reduced snow accumulation, increased severity of floods, shrinkage or loss of lakes etc.)	2	Recurrent droughts, precipitation variability and changes in hydrological conditions affect water availability and ecosystem stability across the region.

Legend:
· **Score 0** (No threats, no impact); Does not pose a threat at this time.
· **Score 1** (Very low threat intensity, Low impact); Minor threat, at present, requiring monitoring but no specific management actions.
· **Score 2** (Moderate threat intensity, Medium impact); Moderate threat requiring specific management actions (to be included in the Protected Areas Management Plans).
· **Score 3** (High threat intensity, High impact); Major threat requiring intensive management actions (to be included in the Protected Areas Management Plans).
· **Score 4** (Very high / Maximum threat, Very high impact).

Methodological note: The Level 1 and Level 2 threat categories follow the IUCN–CMP Threats Classification Scheme (Version 4.0). The intensity scores (0 - 4) are author-derived estimates and are not IUCN ratings. Scores were assigned based on the available regional evidence regarding the spatial extent, recurrence, documented or expected ecological effects, and management relevance of each threat. Score 0 indicates no significant current evidence of impact; Score 1 indicates low and predominantly localized pressure; Score 2 indicates moderate and regionally relevant pressure requiring specific management measures; Scores 3 and 4 indicate high and very high/critical pressures, respectively. A range (1–2) was used where threat intensity varies substantially among locations or ecosystems.

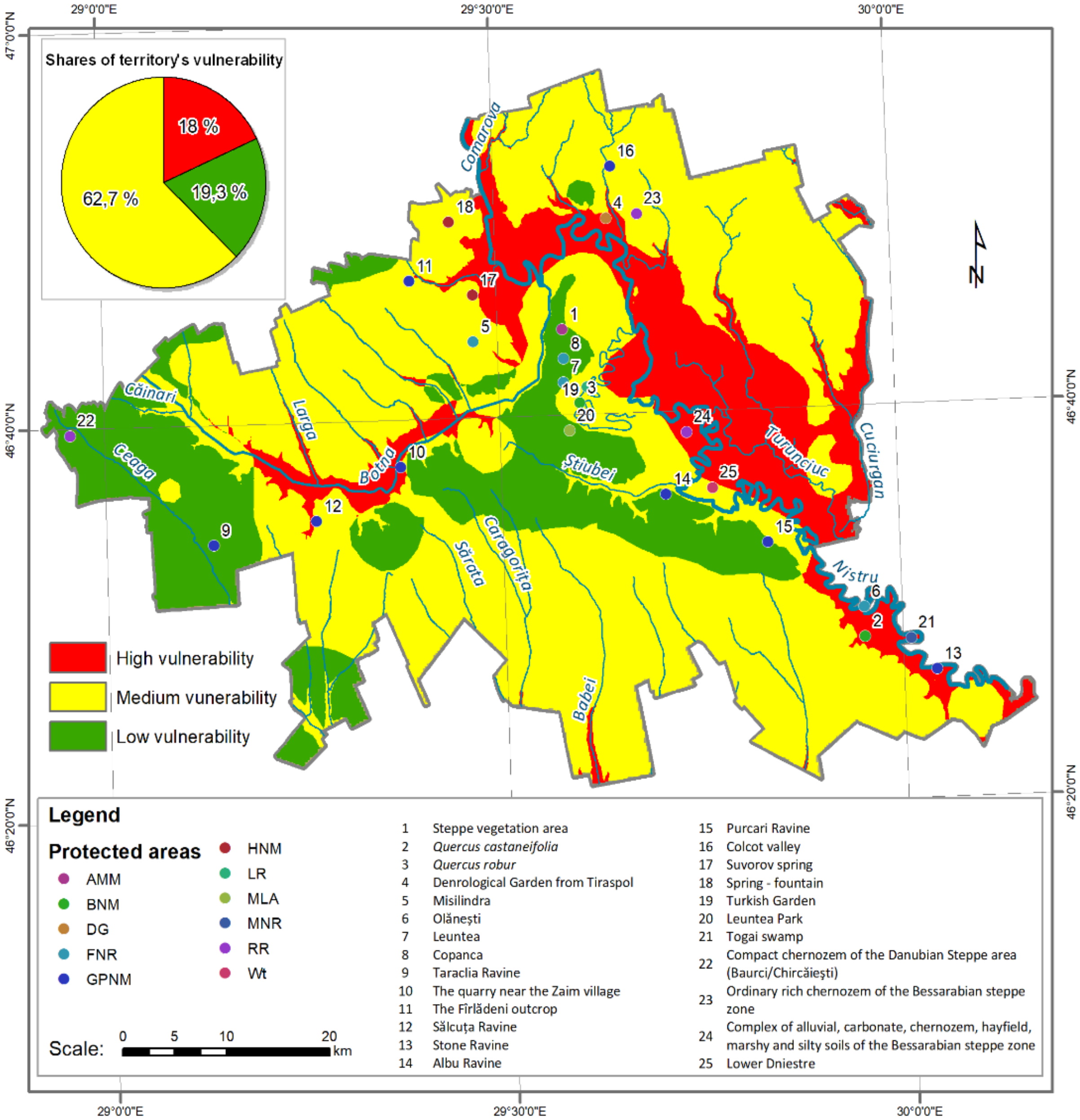


Figure 11. Territorial vulnerability classes derived from the cumulative spatial overlay of abiotic indicators.

Source: Created by the authors.

Based on the cumulative spatial overlay of standardized abiotic indicators, the most vulnerable natural ecosystems are those located in low-altitude territories, especially in the Dniester River floodplain below 50 m, where Mediterranean-type climatic conditions, according to the De Martonne index, and ecological instability, according to the Keco index, overlap. The territorial vulnerability classes shown in Figure 11 represent cumulative spatial vulnerability and should not be interpreted as equivalent to the author-derived 0 - 4 threat intensity scores presented in Table 1. In the study region, three distinct territorial vulnerability zones can be distinguished:

- areas with high vulnerability, characterized by a semi-arid to Mediterranean climate and ecological instability, accounting for about 18% of the study area and predominantly occurring within the Lower Dniester Alluvial Steppe Plain physical-geographical subregion;
- areas with medium vulnerability, transitional one, where natural ecosystems are subject to the impact of environmental pressures, either through the dominance of the climate aridity impact, or through the dominance of the land use and land degradation through exogenous processes (the area covers about 62.7% of the researched territory, with dominance in the physical-geographical subregions Upper Hadjider steppe plan, Lower Bac forest steppe plan and Lower Dniester aluvial steppe plan);
- areas with low vulnerability, where the semi-humid climate prevails, and ecologically stable landscapes (the area covers about 19.3% of the territory, with dominance in the physical-geographical subregion Middle Cogalnic forest steppe plan and a part of Lower Bac forest steppe plan).

Unfortunately, several protected areas that preserve valuable natural heritage fall within the high-vulnerability zone, including the Togai Swamp Nature Reserve, the Olanesti Scientific Reserve, and part of the Lower Dniester Ramsar Wetland.

Data included in this study, serve as basis for future analysis on flora and fauna populations from natural ecosystems. In analysis of the threats will take into account the timing, scope and severity of the threats. For each threat identified in this study, additional information is needed, mainly through direct field studies (during the growing season or specific periods of fauna activity), which would allow the severity of threats and their impact on habitats and local populations.

6. CONCLUSIONS

The present study analyzed threats predominantly induced by abiotic factors on protected natural ecosystems in the South-East Region of the Republic of Moldova, highlighting the important role of ecosystem stability and resilience. It is confirmed that physical-geographical characteristics define an ecosystem's capacity to sustain life, and their alteration (through pollution, fragmentation, climate change, or other human actions) induces biodiversity losses (distribution, abundance, and species adaptation). Although Neogene and Quaternary formations in the region are relatively stable from a geological perspective, they remain vulnerable to erosion risks, especially during prolonged drought periods, which influence both the river's hydrological regime and the stability of floodplain ecosystems. Relief characteristics have led to the formation of areas susceptible to active geomorphological processes (erosion, landslides) and have determined the predominance of ecologically unstable landscapes. From a pedological perspective, the southeastern zone is characterized by the predominance of chernozems, intensively used for agriculture, which explains the high pressure on soil resources and their moderate degree of degradation. The land cover structure confirms the predominantly agricultural character of the region, with a high proportion of cultivated land, in contrast to the relatively limited areas occupied by forests, wetlands, and other natural elements that ensure ecological balance. This distribution increases the vulnerability of natural ecosystems to anthropogenic pressures, ecosystem fragmentation, and biodiversity loss, particularly in the vicinity of protected areas.

Climate change and associated risks are highlighted as the most intense threats to natural ecosystems in the region. Existing data clearly outline local climate aridization trends, which require the identification of appropriate and sustainable measures for conserving the natural heritage of the studied area. Hydromorphological changes of the Dniester River and its tributaries represent another factor threatening protected natural ecosystems, which are formed and sustained primarily through the river's supply of water and nutrients.

The cumulative spatial overlay of abiotic indicators indicates that approximately 18% of the territory is characterized by high territorial vulnerability, while 19.3% falls within the low-vulnerability category. The remaining territory is situated within a transitional zone of moderate vulnerability.

As a result, an integrated approach to geological, pedological, climatic, and anthropogenic factors is essential to ensure geo-ecosystem stability, biodiversity conservation, ecological connectivity and the appropriate management. We recommend this study in the development of management plans for protected areas in the region, including Emerald sites and Ramsar Site, especially in identifying connections between geodiversity and biodiversity, pressures/threats on local biodiversity and conservation measures.

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Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Author contributions

All authors contributed equally to this work. All authors read and approved the final manuscript.

Conflicts of interest

The authors declare no conflict of interest.

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- Research by Posea (2005) and Ielenicz (2003) supports…

If the author's name is not mentioned in the main text then the surname and year should be inserted, in parentheses, after the relevant text. Multiple citations should be separated by semicolon and follow alphabetical order.

- The petrographic composition of the massif explains this type of relief (Ielenicz 2003; Posea 2005).

If three or fewer authors are cited from the same citation then all should be listed. If four or more authors are part of the citation then 'et al.' should follow the first author's name.

- (Ielenicz, Comanescu & Nedelea 2010)
- (Ielenicz et al.2008)

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- (Ielenicz 2003a; Ielenicz 2003b)

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You can introduce the quotation with a signal phrase that includes the author's last name followed by the date of publication in parentheses.

- According to Ielenicz (2003), "quoted text" (p. 199).
- Ielenicz (2003) found "quoted text" (pp. 199-202).

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- (EEA, 2018)

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- On climate change (“Climate and Weather”, 2010) ...
- Guide to Hydrological Practices (2008)

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Yang, P. (Ed.) 2018. *Cases on Green Energy and Sustainable Development.* IGI Global.

Chapter in an edited book:

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Conference proceedings (published):

García Palomares, J. C., Gutiérrez Puebla, J., Romanillos Arroyo, G., & Salas-Olmedo, H. (2016). Patrones espaciales de concentración de turistas en Madrid a partir de datos geolocalizados de redes sociales: Panoramio y Twitter. In *Aplicaciones de las Tecnologías de la Información Geográfica (TIG) para el desarrollo económico sostenible* (pp. 131-139). Actas del XVII Congreso Nacional de Tecnologías de Información Geográfica. Málaga, June 29-30 and July 1. http://congresotig2016.uma.es/downloads/separadas/lt1/García%20Palomares.pdf

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Grahovac, M., Pivac, T. & Nedelcu, A. (2018). Značaj internet prezentacije za razvoj vinskog turizma Banata(Srpski i Rumunski Banat), *SINTEZA 2017, International Scientific Conference on Information Technology and Data Related Research.* (in Serbian with English abstract & summary)

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Hyphenation, em and en dashes

For guidelines on hyphenation, please refer to an authoritative style guide, such as The Chicago Manual of Style (16th ed.) (US English) or Oxford's New Hart's Rules (UK English). Be consistent in your style of hyphenation.

Em dashes should be used sparingly. If they are present they should denote emphasis, change of thought or interruption to the main sentence; em dashes can replace commas, parentheses, colons or semicolons.

En dashes can be used to replace 'to' when indicating a range. No space should surround the dash.

- 10–25 years *OR* pp. 10–65

Numbers

For numbers zero to nine please spell the whole words. Use figures for numbers 10 or higher. We are happy for authors to use either words or numbers to represent large whole numbers (i.e. one million or 1,000,000) as long as the usage is consistent throughout the text.

If the sentence includes a series of numbers then figures must be used in each instance.

- Thermal springs were found in the north of Bucharest at depths of 100, 175, and 230 m.

If the number appears as part of a dataset, in conjunction with a symbol or as part of a table then a figure must be used.

- This study confirmed that 7% of…

If a sentence starts with a number it must be spelt, or the sentence should be re-written so that it no longer starts with the number.

- Fifteen examples were found to exist… *RE-WRITTEN*: The result showed that 15 examples existed…

Do not use a comma for a decimal place.

- 2.56 *NOT* 2,56

For numbers that are less than one a '0' must precede the decimal point.

- 0.29 *NOT* .29

Units of measurement

Symbols following a figure to denote a unit of measurement must be taken from the latest **SI brochure**.

Formulae

Formulae must be proofed carefully by the author. Editors will not edit formulae. If special software has been used to create formulae, the way it is laid out is the way it will appear in the publication.

Tables

Tables must be created using a word processor's table function, not tabbed text.

Tables should be included in the manuscript. The final layout will place the tables as close to their first citation as possible.

All tables must be cited within the main text and numbered with Arabic numerals in consecutive order (e.g. Table 1, Table 2, etc.).

Each table must have an accompanying descriptive title. This should clearly and concisely summarise the content and/or use of the table. A short additional table legend is optional to offer a further description of the table.

The title should be above the table (font 10pt) and the source of the data below (font 10pt).

Example:

Table 1. This is a table. Tables should be placed in the main text near to the first time they are cited

Year	Number of foreign tourists (millions)	Foreign currency cashing (USD billions)	Cashing increase compared to 1950
1950	25,3	2,1	-
1990	410,4	300,4	143,0
2010	940,0	919,0	437,6
2013	1, 087,0	1, 159,0	551,9

Source: UNWTO, 2015

Tables should not include:

- Rotated text
- Images
- Vertical and Diagonal lines
- Multiple parts (e.g. 'Table 1a' and 'Table 1b'). These should either be merged into one table, or separated into 'Table 1' and 'Table 2'.

NOTE: *If there are more columns than can be fitted on a single page, then the table will be placed horizontally on the page. If it still cannot be fitted horizontally on a page, the table will be broken into two.*

Figures

All photographs, maps and graphs have to be named as Figure. The figures have to be enclosed in the text, in their order of appearance and should be numbered consecutively using Arabic numbers. The title (font10pt) has to be below the figure. All figures (photographs and maps) have to be submitted as a separate file. All graphs have to be submitted as a separate file in MS Excel format with all the data needed for making the graph. The file should be named as the number of the figure in the main text. Example: Figure 1, Figure 2, etc. If a figure has been previously published, acknowledge the original source. Example:

(a) **(b)**

Figure 1. This is a figure. Schemes follow the same formatting. If there are multiple panels, they should be listed as: (**a**) Description of what is contained in the first panel; (**b**) Description of what is contained in the second panel. Figures should be placed in the main text near to the first time they are cited. A caption on a single line should be centered.
Source: Adrian Nedelcu, 2014.

Figure 1. Sardinia. La Pelosa beach with marine abrasion forms.
Source: Adrian Nedelcu (2019).

NOTE: *All figures must be uploaded separately as supplementary files during the submission process, if possible in colour and at a resolution of at least 300dpi. Each file should not be more than 20MB. Standard formats accepted are: JPG, TIFF, GIF and PNG. For line drawings, please provide the original vector file (e.g. .ai or .eps).*

Reviewer Suggestions

During the submission process, please suggest three potential reviewers with the appropriate expertise to review the manuscript. The editors will not necessarily approach these referees. Please provide detailed contact information (address, phone, e-mail address). The proposed referees should neither be current collaborators of the co-authors nor have published with any of the co-authors of the manuscript within the last five years. Proposed reviewers should be from different institutions to the authors. You may suggest reviewers from among the authors that you frequently cite in your paper.

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