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Transnational recycling of Australian export waste: An exploratory study

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ABSTRACT

Transnational recycling of waste is a common phenomenon and can have significant environmental and economic impacts on both exporting and importing countries. However, current studies mainly focused on the management of transnational waste recycling in waste-importing countries, and less attention has been paid to issues related to waste-exporting countries. Using Australian export waste data as an example, combining geospatial analysis methods, this study innovatively analyzes the transnational recycling of waste from the perspective of waste exporting countries. The results show that exported waste, assumed to be recycled in the Australian waste statistics, is not fully recycled by waste-importing countries. This study also combines regression analysis to identify factors associated with the destination of waste exports. The results indicate that there is no statistically significant relationship between environmental factors and the location of the destination when exporting waste. Besides, due to the lack of data, waste-exporting countries do not understand the fate of their exported waste and therefore cannot make choices based on the associated environmental impacts. It is recommended that waste-exporting and -importing countries work together to track data so that environmental impacts of exported waste can be better understood.

1. Introduction

Waste is one of the world's most pressing problems. Due to the variety of waste and its reuse value, many countries regard waste as a "misplaced resource" (Chen, 2022; Sileryte et al., 2022). According to its composition, waste mainly includes glass, plastics, paper, tyres, metals (such as aluminum, iron, steel, etc.), TLR (textiles, leather, and rubber), hazardous waste (such as E-waste), organics, etc. Except for some hazardous and mixed wastes, most waste can be recycled, and some of them (e.g., metals and some forms of plastics) have a very high economic and resource recovery value (Jadhao et al., 2022; Jiang et al., 2022).

Based on this, more and more countries have started strengthening the management and recycling of their wastes to enhance the use of resources and energy (Magazzino and Falcone, 2022; Oyedotun and Moonsammy, 2021; Roy et al., 2022; Tian et al., 2022). However, it is contingent on each country's situation such as energy costs, labor costs, and recycling capacity.

In many developed countries, it is not unusual that a certain proportion of waste is exported to developing countries for recycling. Global waste recycling has become an increasingly common phenomenon (Liu et al., 2018). According to the *Australian National Waste Report 2022* (The Department of Climate Change, 2022), around 4.5 Mt/yr of recyclable waste has been exported for recycling since 2011. Some types of waste are exported in high proportions. For instance, in 2022, more than half of Australia's waste metals were shipped out of the country for recycling, while the export rate of waste paper was 26% (The Department of Climate Change, 2022). Australia's waste recycling relies heavily on the export of waste to other countries. This phenomenon is similar to the United States and many developed European countries (Liu et al., 2018). Therefore, Australia's problems in exporting waste management can provide valuable information for other countries.

The benefits associated with transnational recycling of waste are well recognized. For waste exporting countries, exporting waste can enhance the reuse of resources and provide low cost sources of materials. At the same time, exporting countries can protect the local natural environment by reducing waste from being stockpiled or landfills. For waste importing countries, many wastes have high economic value and can be processed into new products. This can contribute to the economic and manufacturing development of the waste importing country. For example, in many countries, recycling imported waste is an industry that can effectively increase local employment. In addition, the transnational recycling of waste can contribute to a global circular economy that is

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conducive to regional or global sustainable development.

The transnational recycling of waste, however, also creates many environmental problems. Since 1970s, the growing level of environmental awareness and scrutiny have resulted in increased disposal costs especially for hazardous waste. As a result, the last decades have witnessed hazardous waste was sent to counties with lower level of environmental awareness and less stringent regulations (UN environment programme, Basel convention, 2023). For this reason, in 1989, several countries worked together to establish the *Basel Convention* to strengthen the global import and export control of hazardous wastes, with the aim of combating the "toxic trade"(UN environment programme, Basel convention, 2019). Australia also ratified the *Basel Convention* in 1992. However, the environmental impact of transnational waste recycling cannot be completely eliminated by merely regulating the transnational trade of hazardous waste. For instance, when large amounts of solid waste are recycled across borders, most of it is transported by sea. This results in significant carbon emissions from transportation, which has a negative impact on the environment. Besides, during the waste recycling process, most of the recycling processes consume large amounts of electricity. However, the mainstream waste importing countries are currently developing countries in Southeast Asia. In these countries, the use of clean energy is low due to the limitations of local economic and social development levels. Therefore, these countries consume higher amounts of traditional fossil fuel when recycling waste, resulting in global environmental impacts through climate change. The non-carbon emissions from the recycling process can also harm the local environment.

Therefore, there is an urgent need to examine the issues associated with waste exports from developed countries. Vast majority of existing studies focused on the impact of waste importing countries' policies on exported waste. For example, a number of studies investigated China's waste import ban in 2017, analysing its effects on the amount and type of waste exported from different countries (Huang et al., 2020; Kumamamaru and Takeuchi 2021; Sun and Tabata 2021; Wang et al., 2020). There are also studies focusing on waste policies in Vietnam, Malaysia, India, and other countries (Laha, 2022; Moh and Abd Manaf, 2014; Nong et al., 2020; Pani and Pathak, 2021). However, transnational recycling of waste is a systematic process of resource recycling. As waste sources, waste exporting countries are also part of the recycling ecosystem that deserve attention. Analysis of waste exporting countries' current situation can provide useful inputs for the optimization of transnational solid waste management systems. Managing the international waste cycle at the source can be facilitated by analyzing the types and quantities of exported waste and their export destinations from the perspective of waste exporting countries. However, there is a lack of studies that analyze the status of waste exports from the perspective of waste exporting countries. This is not conducive to a systematic understanding and analysis of transboundary recycling of waste. This is also not beneficial in promoting better waste management in different countries to contribute to regional sustainable development.

This study is undertaken from the perspective of waste exporting countries to address this problem. By using Australia as an example, this study analysis the exported waste. This study aims to understand: 1) the current status of waste recycling transnationally management, by using Australia as an example, and 2) what are the drivers of the destination of waste being exported. This study uses spatial statistical analysis, ordinary least squares regression (OLS), and geographically weighted regression models (GWR) to explore the status and spatio-temporal characteristics of exported waste in Australia from 2018 to 2021. This study also uses multiple linear regression models to investigate the association between exported waste type, quantity, and location with economic and social influences. Findings provide theoretical support for the transnational recycling waste management.

2. Literature review

2.1. Transnational recycling of waste and its related policies

Among the studies on transnational recycling of waste, many focus on waste's environmental and economic impacts on the importing countries. For example, Hung et al. (2015) examined the persistent organic pollution of waste metal copper in the recycling process in the countries where the waste is recovered. Gündoğdu and Walker (2021) explores the impact of the continued import of plastic waste on the marine environment in Turkey since 2018. In addition, different models were adopted to analyze the economic value of recycled waste. For instance, Broberg et al.,(2022) analyzed the economic benefits of incinerating imported waste, using Sweden as an example. They found that incinerable imported waste can effectively replace some fuel. Incineration of imported waste is beneficial for both enhancing the full utilization of resources and cost savings. In general, although some types of waste (e.g., incinerable waste) can be recycled transnationally to enhance recycling and reuse of resources, most of the waste still cause harm to the local environment due to the recycling process and the technology level of the waste importing countries. Therefore, transnational waste recycling was considered as pollution transfer from developed to developing countries (Liu et al., 2018).

In addition, some studies focused on global waste flows. Such studies paid more attention to the waste policies of various waste importing countries and analyzed the impact of these policies on global waste flows. In recent years, with the continued focus on environmental problems and the rapid development of the circular economy, many developing countries have tightened up their waste recycling laws and standards (Winans et al., 2017). For example, in 2017, the Chinese government announced a ban on the import of 24 types of waste (Walker, 2018). This policy has put tremendous pressure on developed countries around the world. Moreover, countries such as Malaysia, Vietnam, India, and Indonesia have also issued bans on some types of waste (Liang et al., 2021). Mixed waste was the first one to be concerned and banned, followed by e-waste. Besides, many countries have enhanced the recycling of domestic waste plastics and strengthened the regulation of imported plastics. For instance, in its 2016 policy, Indonesia would only accept processed plastics (post-waste) in flake, chip, or pellet form (Liang et al., 2021). Such policies force developed countries to sort and pre-treat their exported waste according to the policies of major waste importing countries. In general, current policies for transboundary waste recycling are becoming increasingly stringent. The waste that can be transported and recycled across borders is shifting from mixed waste to separated waste with high economic value.

2.2. Drivers of waste recycling across regions

According to the destinations, cross-regional waste recycling can be classified into domestic and transnational. There are a large number of factors that affect the domestic cross-regional recycling of waste. For example, Lingling and Hongping (2022) found that recycling prices and tax policies significantly impact the waste flow. This is supported by other studies (Deswal and Laura, 2018; Gilardino et al., 2017; Karimi et al., 2022) that the choice of waste recycling location is related to the local waste recycling capacity. Waste is more likely to flow to countries or regions with large recycling capacity. Other studies have found that the level of economic development and environmental priority in different areas can also impact the destination of waste flows (Somani and Srivastava, 2021). Overall, cross-regional waste flows are influenced by various factors, including environmental, economic, and social development levels.

Unlike domestic cross-regional waste recycling, fewer studies are related to factors to the transnational waste recycling. Current research on transnational waste recycling has mainly focused on the impact of waste recycling policies in different countries (Huang et al., 2020;

Kumamamaru and Takeuchi 2021; Sun and Tabata 2021; Wang et al., 2020; Laha, 2022; Moh and Abd Manaf, 2014; Nong et al., 2020; Pani and Pathak, 2021). In recent years, as environmental problems continue to be emphasized, some studies have also begun to consider the carbon emissions generated when transnationally transporting waste. For instance, the importing countries' shipping distance and energy cleanliness may impact the choice of waste recycling destination (Sun and Tabata 2021). These factors are summarized in (Table 1).

3. Methods and data

3.1. Data sources

The primary data for this study were retrieved from the *National Waste Report 2018, 2020 and 2022* (Department of the Environment and Energy., 2018,Department of Agriculture, Water and the Environment., 2020; The Department of Climate Change, 2022). The National Waste Report is compiled by The Department of Climate Change, Energy, the Environment and Water in Australia and is updated every two years. Data included in this report was obtained from state and territory governments, which were collected from waste operators and local governments (Department of the Environment and Energy., 2018, Department of Agriculture, Water and the Environment., 2020; The Department of Climate Change, 2022). This report covers Australian waste-related data with high data reliability. In terms of exported waste data, this report has more detailed information (including the type of waste, the total amount of waste sorted, when, and where it was exported) than the Australian export data published by the Australian Bureau of Statistics.

Table 1
Common influencing factors of waste exporting.

	Indicator	Description	References
Economic	GDP, GDP per capita, PPP, PPP per capita	The less developed the economic development, the more likely it is to receive waste	(Greco et al., 2015; Kinobe et al., 2015; Richter et al., 2018)
	Recycling fees, recycling subsidies, recycling costs, labor costs, standard hourly wage, education level	The lower the cost and the higher the subsidy, the more waste is received in the area.	(Behi et al., 2022; Kinobe et al., 2015)
Social	Labor force level, employment rate, unemployment rate	The higher the labor level, the more likely to receive waste in the area	(Cavdar et al., 2016; Greco et al., 2015)
	Industrial development level, manufacturing development level, number of recycling enterprises, recycling capacity	The higher the level of industrial development, the stronger the recycling capacity of the region, more likely to receive waste	(Cheung and Pachisia, 2015; Llorente-González and Vence, 2020)
	Transportation distance, ease of transportation, easiness of transportation	The easier the area is to transport, the more likely it is to receive waste.	(Sun and Tabata, 2021)
Environmental	Energy cleanliness/ environmental policies, environmental attitudes, environmental regulation	Different considerations for different studies	(Calcott and Walls, 2005; Maiurova et al., 2022; Sun and Tabata, 2021)

Information about policies in Australia's major waste importing countries was obtained from the relevant literature (Huang et al., 2020; Kumamamaru and Takeuchi 2021; Sun and Tabata 2021; Wang et al., 2020; Laha, 2022; Moh and Abd Manaf, 2014; Nong et al., 2020; Pani and Pathak, 2021). The national economic and social data were collected from the *World Bank*.

3.2. Research methods

3.2.1. Space center of gravity transfer curve

The spatial center of gravity shift curve is used to describe the direction of the space-time shift of things and their characteristics. This method has been employed to analyze the space-time variation of the research problem (Ge and Feng, 2010; Man et al., 2021; Sun et al., 2015). This study adopted the standard deviation ellipse SDE method in ArcGIS for plotting, where the range of SED indicates the main spatial distribution area of different kinds of waste exported, and the center indicates the relative position of the exported waste distribution. In this study, the spatial center of gravity shift curve is used to analyze the variation of the export location of different kinds of exported waste.

3.2.2. Spatial divergence correlation

This study uses OLS and GWR models to explore the relationship between the amount of waste exported from Australia and economic and social factors in the destination countries at different periods.

OLS is a parameter estimation method used to determine the best-fit straight line for the ordinary linear regression equation with the following equation.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \varepsilon_i \tag{1}$$

In Eq. (1), $x_i (i = 1,2,\ldots,n)$ indicates the different influencing factors of each waste importing country; y indicates the amount of waste exported from Australia to each waste importing country; β_0 is a constant term; $\beta_i (i = 1,2,\ldots,n)$ is the coefficient of each variable; ε_i is a random error term.

GWR is based on a general linear model that embeds the spatial location of the data into the equations as follows.

$$y = \beta_0(u_i, v_i) + \Sigma \beta_k(u_i, v_i) x_{ik} + \varepsilon_i \tag{2}$$

Eq. (2) in (ui, vi) denotes the spatial coordinates of the i sample point; β_k(ui, vi) indicates the k regression parameter on the i sample point; ε_i is the random error term where the degree of explanation of the dependent variable by the independent variable in the model is characterized by applying R^2.

In this study, the spatial location in the GWR model is the geographical distance between different waste importing countries and Australia. The R^2 of the GWR model will be significantly higher than the R^2 of the OLS model if geography impacts the amount of waste exported from Australia.

3.2.3. Multiple linear regression model

A regression analysis that has two or more independent variables and seeks a relationship between them and the dependent variable is called a multiple regression model (Oukawa et al., 2022). The relationship between the independent and dependent variables may be diverse. A model that uses linear correlation as a relationship is called a multiple linear regression model.

A phenomenon is often associated with multiple factors. It is common to use various linear regression models to understand the influence of numerous factors (independent variables) on this phenomenon (dependent variable). The R^2 of the model can be used to assess the model's reliability, while the regression coefficient of each independent variable can reflect its importance. The R^2 varies widely across research areas. For instance, in experimental studies, the R^2 can reach 0. 92

(Yirga, 2019), while in studies related to social phenomena, the R^2 may be as low as 0.25 (Shi et al., 2021).

Multiple linear regression models are widely used in environmental research. For example, Yang and Li (2020) used this model to analyze the factors influencing the urban thermal environment, and Dos Santos et al. (2022) used this model to analyze the impact of the environment on human health. This study used the multiple linear regression model to investigate factors influencing the destination of Australian waste exports.

4. Status of Australia's export waste

4.1. Composition and generation of Australia's export waste

According to data from the *National Waste Report 2020* (Department of Agriculture, Water and the Environment., 2020) 39.42 million tonnes of waste were recycled in 2021, of which 4.5 million tonnes (approximately 12%) were shipped out of Australia for recycling. Export waste has fluctuated over the past 10 years, from about 280,000 tonnes in 2007 to over 40 million tonnes in 2019. Meanwhile, the proportion of exported waste to total recycled waste has increased during the study period. In 2007, less than 10% of waste was exported, while in 2019, more than12% of waste was exported for recycling Fig. 1.

4.2. The fate and flow of Australia's export waste

The fate of Australia's export waste is not clearly documented. Australia's export waste is mainly metals and paper, which have a high recycling value. A common assumption made in official statistics is that export waste is recycled in the waste importing country (Department of the Environment and Energy., 2018, Department of Agriculture, Water and the Environment., 2020; Green Industries SA,2021). However, whether or not these wastes are recycled is determined by the recycling process and waste management in the waste importing country. Recently, some studies found that exported wastes are not well reused in the importing countries, and some are even dumped illegally (Amechi and Oni, 2019; Gündoğdu and Walker, 2021). This can seriously pollute the environment in waste importing countries and is not consistent with the intention of waste exporting countries to protect the environment. Therefore, understanding the fate of waste after export is essential for better waste management. This study reviews the recycling rates, reproduction products, and policies for different types of waste in Australia's major waste importing countries.

Waste metal took the largest share in terms of Australia's exporting waste. In recent years, waste metal has become popular in more and more countries (Corder et al., 2015; Reck and Graedel, 2012). In many countries, waste metal is considered as a substitute for virgin metal. Since waste metal is cheaper than virgin metal (pig iron, raw steel, etc.), many metal smelters buy waste metals directly for smelting. Iron from waste metal is used, as an example, to produce steel bars of different thicknesses. Due to the high value of the waste metal, it has a high recycling rate in many countries and regions. Some studies found that some types of metal (e.g., lead, copper and manganese alloys) can be recovered up to 95% (Tran and Salhofer, 2018). In general, the recovery rate for most waste metals is around 60%.

Paper, the second largest proportion of Australian exported waste, is handled differently in different importing countries. Reprocessing waste paper can result in varying levels of fiber losses, depending on the grade. Thus, not all exported paper can be processed secondarily into products by the waste importing country (Berglund and Söderholm, 2003). In India, for instance, only 60–90% of imported waste paper can be produced into remanufactured paper (e.g., containerboard, cardboard, and paper bags). About 20% of waste paper is used as an alternative fuel for recycling energy (Jha, 2018; Staub, 2020).

Among all kinds of waste, there are most stringent policies on importing plastics. Many countries are gradually reducing or even banning the import of plastic waste from other countries because of sufficient raw materials. For now, the primary plastic waste importing countries (such as India, Indonesia, and Malaysia) have many informal plastic recycling organizations due to their waste management deficiencies (Laha, 2022). To save costs, these organizations sent part of their plastics to landfills. According to the literature, the recycling rate of waste plastics is not higher than 50% in many plastic importing countries (Chen et al., 2021; Liang et al., 2021; Neo et al., 2021). Recycled plastics are processed into different products depending on their types (e.g., packaging items, wrapping paper, carpet fibres, etc.) (Nyika and Dinka, 2022).

Under the *Basel Convention*, untreated tires are classified as hazardous waste (UN Environment Programme, Basel Convention, 2019). However, because tire components do not have hazardous characteristics, primary treated tires are allowed to be exported. The waste tires exported from Australia are all preliminarily treated. Even though, waste tires may still pose a risk to the environment and humans due to the processing and transportation process. Therefore, waste tires are well monitored and managed in many countries. According to *Domestic / International Standards for Waste Tyres and Market Information* (MRA Consulting Group, 2021), waste tires exported from Australia are retreaded for use as passenger car and SUV tires in Spain, Portugal and Italy. However, none of these three countries is a major recipient of waste tire exports from Australia. Most waste tires are received by Southeast Asian countries (e.g., Malaysia, Indonesia, Vietnam, etc.). After reviewing the literature, it was found that, depending on the process, waste tires can be converted into different products (e.g., recycled rubber, crumb rubber, crumb rubber-modified asphalt,

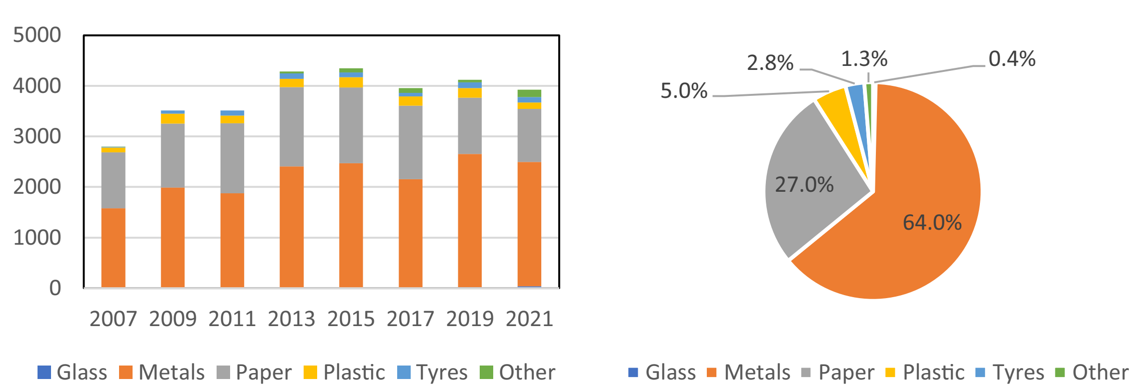

Fig. 1. Generation and compositions of export waste in Australia. In terms of weight, about 64% of Australia's export waste is metal, followed by 27% paper (including cardboard) and 5% plastic. Waste such as glass, tyres, and others (textiles, e-waste, etc.) have a small percentage, contributing less than 5%.

recycled carbon black, and pyrolysis oil). The recycling rate of waste tires varies from country to country, but, due to the strong secondary processing and utilization value of waste tires, the recycling rate is generally high, and even exceeds 90% in some countries (Karaağaç et al., 2017; Sienkiewicz et al., 2017; Ramarad et al., 2015; Valentini and Pegoretti, 2022).

In order to achieve a sustainable future, Australia is proposing in the 2019 *National Waste Policy Action Plan (*Australian Government,2019*)* to strengthen the management of exported waste. Under the requirements of the Australian *Recycling and Waste Reduction Act (*Australia Government,2020*)*, exported glass is classified as oven-ready and non-organizable. Currently, mainstream waste glass is recycled in a similar way. Once the glass enters the recycling plant, it will be color sorted, crushed and decontaminated. It is then sent to a bottle manufacturing plant to be melted at high temperatures, and then it will go into new glasspackaging. Packaging and non-packaging glass cannot be mixed and heated (because of the different melting points). Waste glass needs to be sorted before being recycled. Following Australian regulations, the exportable waste glass must be clean crushed glass that can be used in the furnace or 'furnace ready'.. In addition, glass that can or cannot be used in the furnace have different numbering codes. This classification can help the importing countries to make different types of waste glass into different products. In general, glass can be made into new glass containers. There are also some types of glass that are processed into abrasives, construction materials, decorative materials, or filters. In terms of recycling rate, it varies significantly from country to country. For instance, China's glass recycling rate is only 20%, while India's can reach 45% (Ferdous et al., 2021).

In addition, waste exports from Australia contain a small proportion of mixtures (textiles, rubber, etc.). If recycling this type of waste, additional sorting is required. This would consume a significant amount of time and labor. Therefore, most of the mixed waste is landfilled in the importing country (Ferdous et al., 2021) (Table 2).

Table 2
The flow of Australia's exported waste.

Source Stream	Waste type	Percentage*	Recycling rate**	Recycled products
Australia export waste	Waste metal	64%	Near 60%	Substitute raw metal (making steel bars, etc.)
	Waste paper	27%	60–90%	Remanufacturing of paper (containerboard, paperboard, paper bag, etc.)
			Near 20%	Alternative fuel
	Waste plastic	5%	<50%	Remanufacturing of plastic (e.g., wrapping items, wrappers, carpet fibres, etc.)
	Waste tyres	2%	>90%	Reclaimed rubber; crumb rubber; crumb rubber modified bitumen; recovered carbon black; pyrolysis oil
	Waste glass	2%	20–45%	New glass containers; abrasives; construction materials; decorative materials; filters
	Mix waste	<2%	–	–

* The percentage of exports of different types of waste is an average value for the period 2019–2021.
** The recycling rate is derived from the averaging the recycling rate of this kind of waste by the major receiving countries (sorted by the amount of waste received, totalling more than 80% of the export weight of this kind of waste). The time span is from 2019 to 2021.

4.3. Transboundary flow of Australia's exported waste

In Australia, some waste is transported and exported overseas for recycling. The National Waste Report and the website of the Australian Bureau of Statistics provided some statistics on exporting waste. These data reveal the flow of some waste outbound for recycling. The export destinations vary according to type of waste.

Waste metal has the largest export amount. Australia's waste metals are mainly iron and aluminum products with high economic value. Therefore, this kind of waste is not currently a prohibited product for import in any country. The export destination of this kind of waste is less influenced by the policy factors of the importing countries. The map shows that most of the metal is exported to South Asia; Vietnam (24%) occupies the largest proportion of waste metal. According to the observation of the spatial center of gravity shift curve, it is found that the major importing countries of waste metals have shown a geographical shift towards the northwest in recent years. In terms of countries, Bangladesh is gradually increasing its imports of Australia's waste metals, from 7% in 2018 to 17% in 2021 (Fig. 2).

Waste paper has the characteristics of easy recycling and high economic value. Indonesia (41%) and China (18%) are Australia's main waste paper importers. However, the spatial center of gravity of Australian paper exports is shifting to the west during the study time. Combined with the waste flow map, it can be found that India is receiving an increasing amount of waste paper, while China is importing significantly less paper waste. After reviewing the import policies of the major waste receiving countries (China, India, Indonesia, Singapore, Malaysia, and Vietnam), this study found that Australia's export of sorted paper is not prohibited in any country. Therefore, the importing countries' policies cannot directly influence Australia to change the destination of exported waste. The reasons for the change in the flow of Australian exported waste paper in recent years warrants further analysis (Fig. 3).

Compared with other wastes, waste plastic is of high concern because of its harmful effects on the environment. According to the waste export flow map, it can be observed that Malaysia (16%), China (14%), Turkey (15%), Indonesia (5%), and Spain (5%) are the main waste plastic importing countries. Among them, Indonesia and China have reduced the amount of waste plastics received during the study period. By contrast, Turkey, Malaysia, and Spain have increased their imports. Together with the spatial focus of plastics exports, in recent years, Australia's export destinations for waste plastics have evolved from the concentrated Pacific region to decentralized India and other countries. The geometric focus of exported plastics destinations has shifted to the west, indicating that countries west of Australia, e.g. Turkey and Spain have received more waste plastics in recent years (Fig. 4).

The export flow map for waste tyres differs from other waste streams. The spatial center of gravity ellipse and center of gravity point of waste tyre exports did not show a significant location shift. This phenomenon means that the amount of waste tyres received by each country does not change significantly over time. The main countries receiving Australian waste tyres India, Malaysia, South Korea, and the United States. After reviewing the relevant policies of major waste tyre importing countries, this study found that these countries have strict regulations on tyres, and the regulations have been updated in recent years. This reduces the likelihood that waste importing countries will revise their waste import policies again in the short term. Therefore, there may not be a major shift in the major export locations for Australian waste tyres in the coming years (Fig. 5).

The location of waste glass exports has changed significantly during the study period. In 2018 and 2019, Indonesia was the main recipient of Australian waste glass exports. However, after 2019, waste glass started to be imported by more countries. Countries such as New Zealand (30%), Vietnam (6%), and the Philippines (14%) have increased the amount of waste glass they receive. The spatial center of gravity ellipse for waste glass exports also significantly changes over time. The

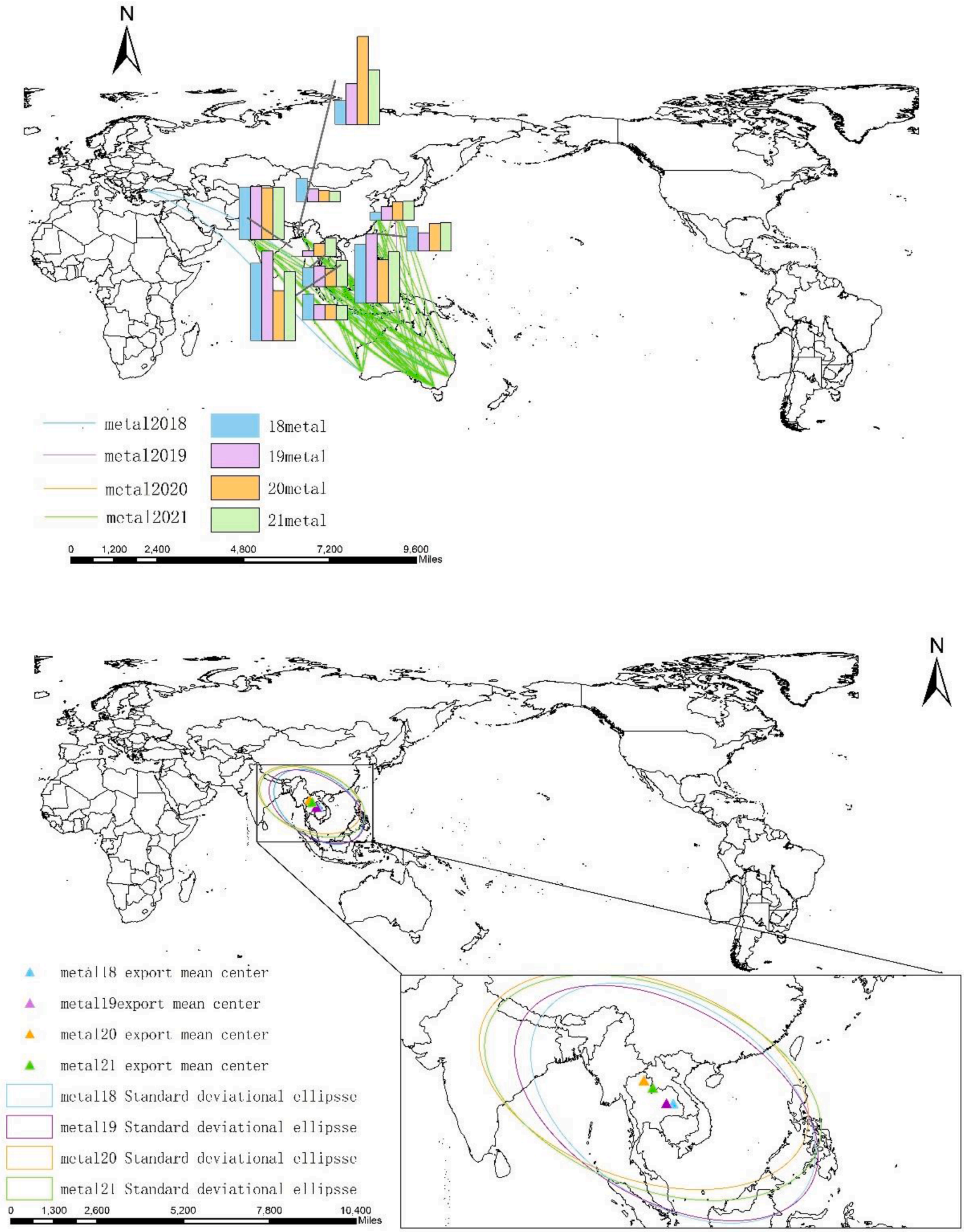

Fig. 2. Australia's waste metal exporting.

progressively larger spatial center of gravity ellipse indicates a gradual dispersion of export locations. This phenomenon shows that more countries are beginning to receive waste glass exported from Australia (Fig. 6).

Maps show that the destination of Australian exported waste has shifted westward over time (e.g., Spain, Bangladesh). India, Indonesia, and Malaysia are the main waste importing countries. However, after reviewing the relevant policies of waste export destination countries

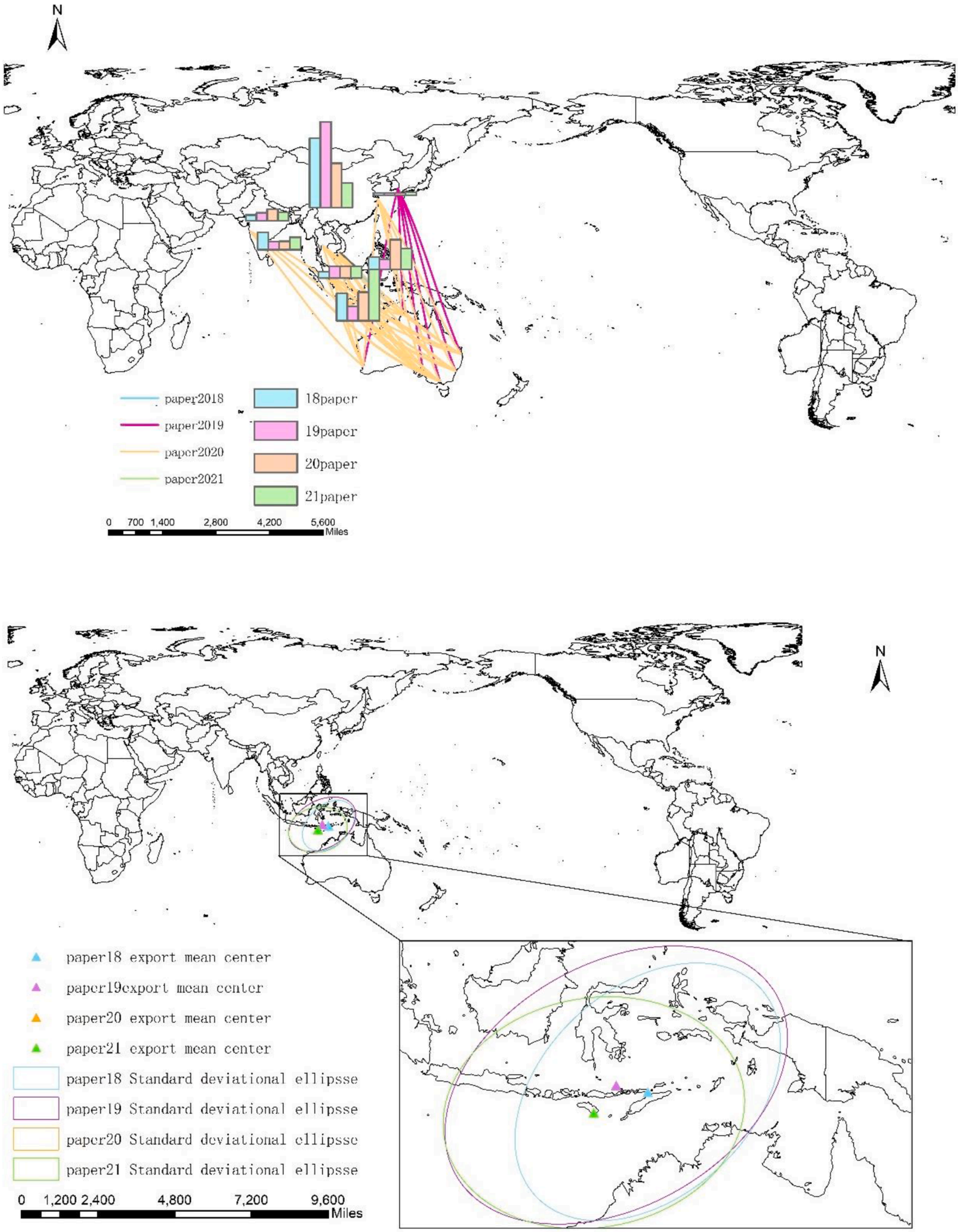

Fig. 3. Australia's waste paper exporting.

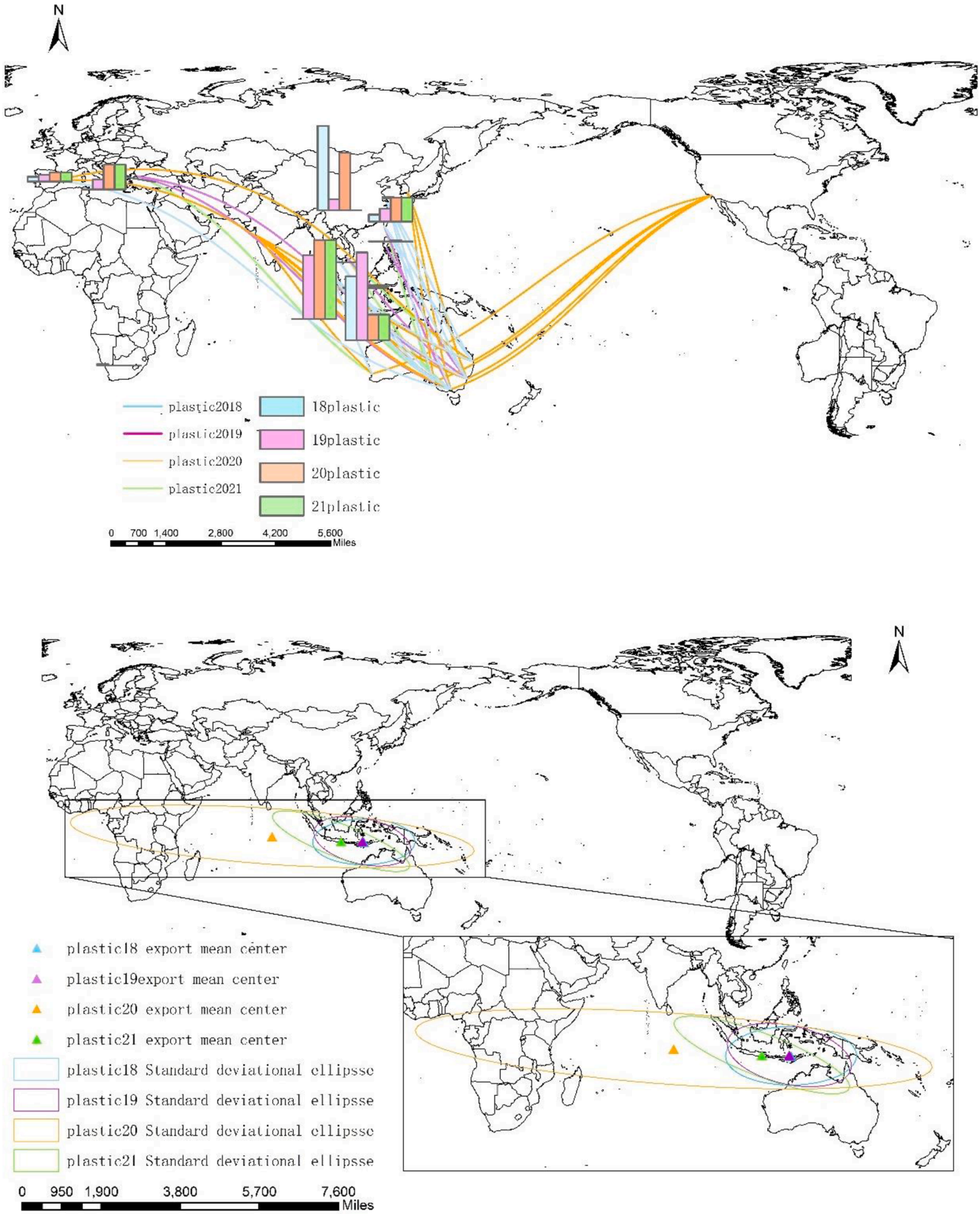

Fig. 4. Australia's waste plastic exporting.

(Ahluwalia and Patel, 2018; Ministry of Commerce of the People's Republic of China, 2018; National Environment Agency, 2014; (Ministry of Environment, Forests and Climate Change Government of India, 2016); Sang-Arun and Bengtsson, 2012; Sanjeevi and Shahabudeen, 2015; Wichai- Utcha and Chavalparit, 2019), this study did not find any significant policy differences between countries. Several types of wastes involved in this study were not explicitly banned or restricted in any of the waste importing countries. Therefore, it can be concluded that the waste import policies of different countries do not seem to directly impact the amount and destination of waste currently exported from Australia.

So, why is Australian exported waste more likely to be shipped to

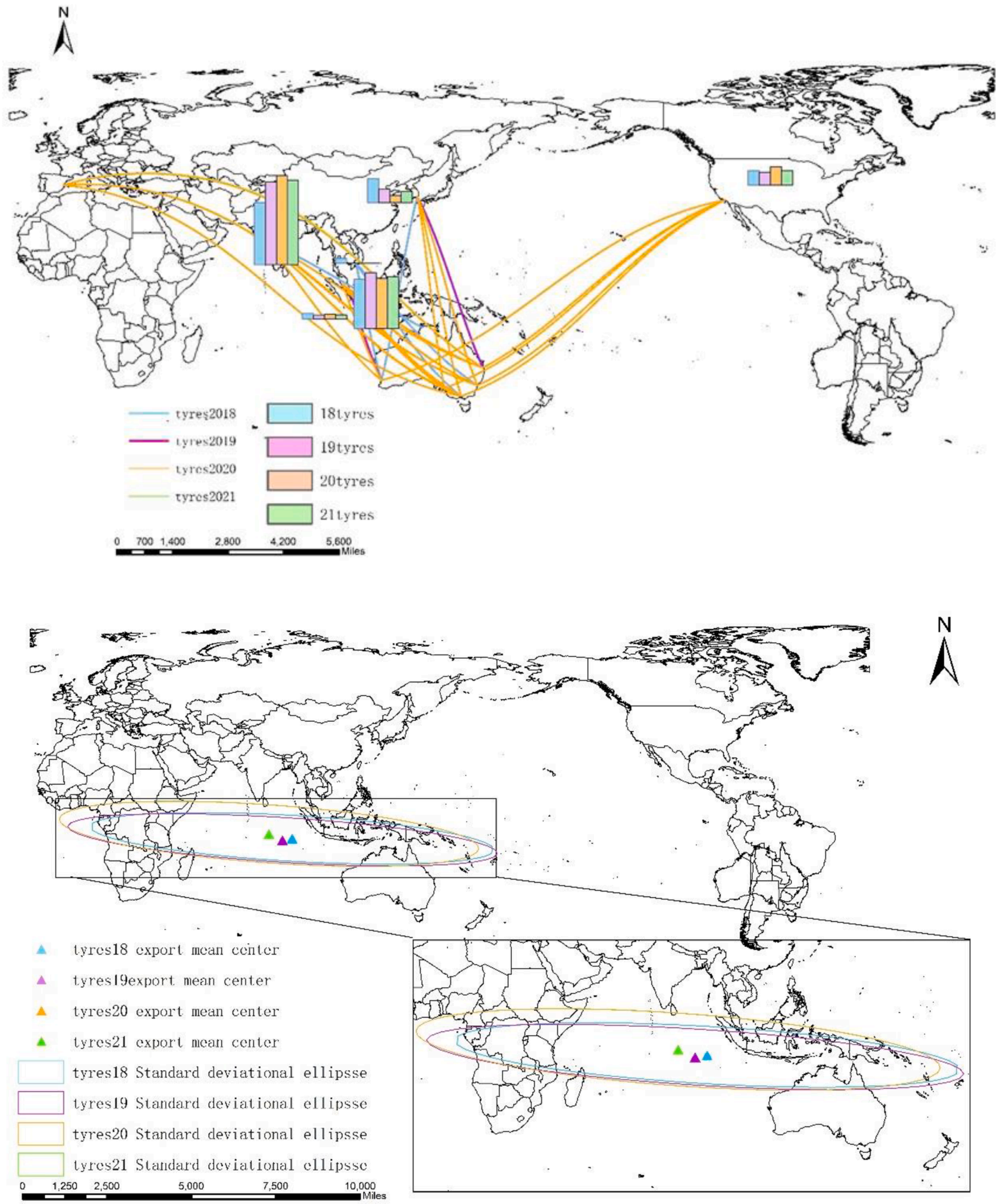

Fig. 5. Australia's waste tyre exporting.

these countries? This study used a geographically weighted regression (GWR) model and an ordinary least squares(OLS) model to investigate this question. The model shows the following results. In Table 3, the GWR and OLS models show the same for different types of waste. This indicates that geographically weighted regression does not play a statistically significant role. The correlation between the amount of Australian waste exported and the distance to the destination is low. This finding is inconsistent with the results of some studies. For instance, Sun & Tabata (2021) studied plastic exports from Japan. They found that Japan would export more waste to countries closer to Japan if the policy of the receiving countries were allowed. This is because it takes care of the costs associated with transportation and reduces carbon emissions from transport, which can be helpful for the sustainability of the region. This study, however, found that more of Australia's waste is

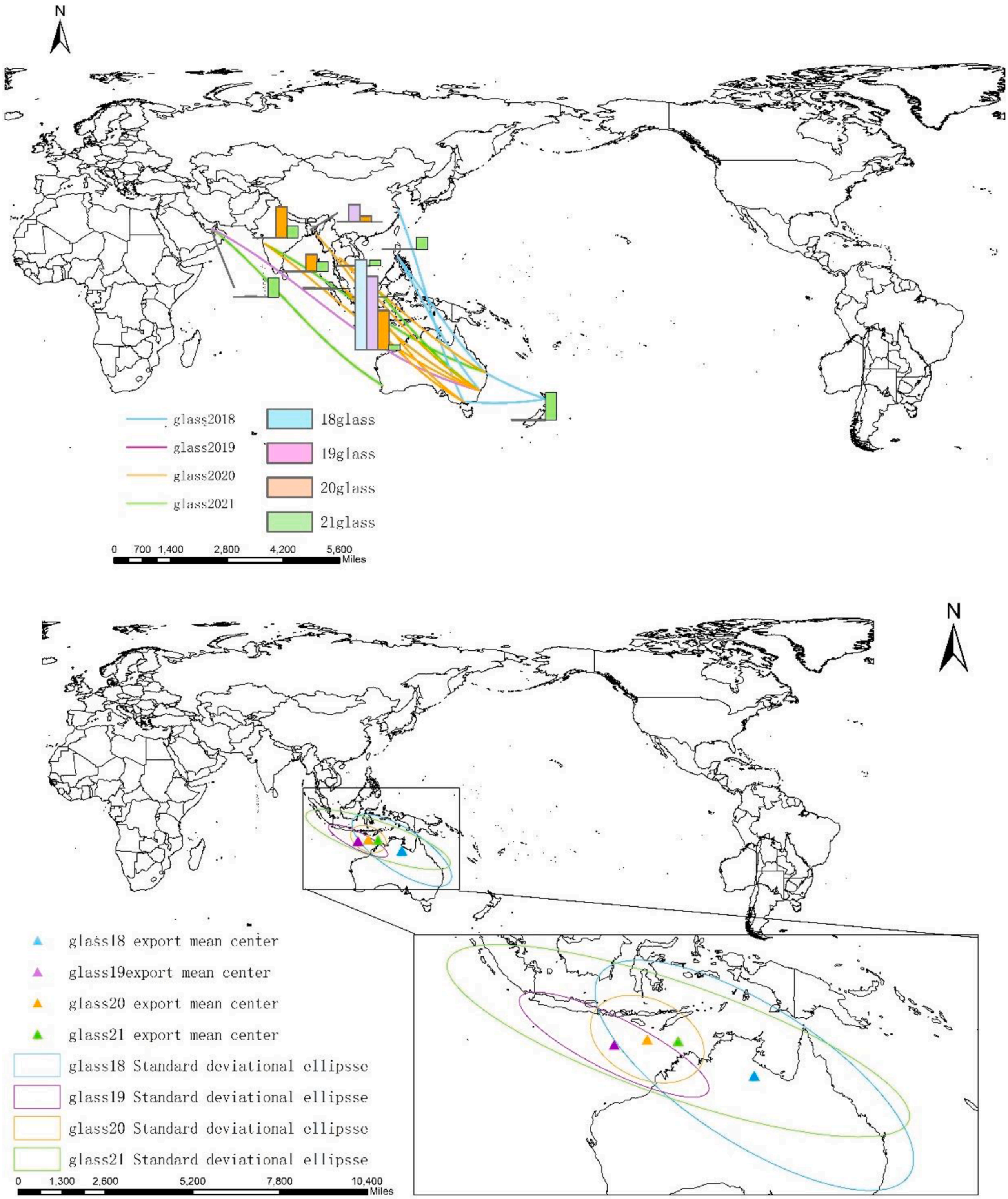

Fig. 6. Australia's waste glass exporting.

shipped to countries such as India, Vietnam, and Malaysia. Some kinds of waste have even been sent to the United States and Spain. Countries closer to Australia, such as New Zealand, Indonesia, and Singapore, received smaller amounts of waste instead. Therefore, it is crucial to understand what are influencing factors to the destination of Australia's exported waste (Table 3).

5. Factors associated with the location of Australia's exported waste

Following Tables 1, 7 factors are selected to examine the influencing factors to the destination of Australia's exported waste (see Table 4).

The time span of this study is from 2018 to 2021 and the period of this study falls on COVID-19. However, after reviewing the post-2020 waste management policies of Australia's major waste-importing

Table 3
The explanation degree of different influencing factors on the quantity of exported waste under the OLS model and GWR model (R^2).

	OLS2018	GWR2018	OLS2019	GWR2019	OLS2020	GWR2020	OLS2021	GWR2021
Metal	0.30	0.30	0.20	0.20	0.40	0.40	0.15	0.15
Paper	0.70	0.70	0.79	0.79	0.60	0.60	0.32	0.32
Plastic	0.43	0.43	0.32	0.32	0.41	0.41	0.13	0.13
Tyres	0.06	0.06	0.15	0.15	0.16	0.16	0.21	0.21
Glass	0.13	0.13	0.18	0.18	0.11	0.11	0.09	0.09

countries, no policy changes directly related to COVID-19 were identified. Therefore, this study did not consider policy factors related to COVID-19.

According to the literature, a large amount of plastic waste was generated during COVID-19 (Abhilash and Inamdar, 2022; Mallick et al., 2021; Mohana et al., 2023). However, due to data limitations, it is difficult to identify how much of the waste plastic exported from Australia was generated during COVID-19. Therefore, this study did not consider the effect of COVID-19 on exported waste (Table 4).

5.1. Factors related to waste metal

The indicators selected in this study can explain well the location where waste metals are exported, with a model fit of 0.79. In this model, the difference in GDP between importing and exporting countries (X1), manufacturing value added in waste receiving countries (X3), unemployment rate (X4), and labor intensity (X5) can highly and significantly affect the amount of waste metal exported ($p<0.01$). Carbon emissions from the recycling process (X6) and employment rate (X7) can significantly affect the amount of waste metal exported ($P<0.05$). Analyzing the coefficients of the indicators, this study found that 3 indicators (X1, X3, X5) correspond to negative coefficients. These 3 indicators are related to the level of economic development, the level of industrial development, and the labor intensity of the waste importing countries. This phenomenon shows that the places receiving more waste metal from Australia have a large gap with the economic development level of Australia, a low level of local manufacturing development, and low local labor intensity. Combined with the transportation map in the previous section, this study found that most waste metal is currently being shipped to Southeast Asian countries with low levels of industrial development.

After reviewing the literature, this study found that Southeast Asian countries, represented by Vietnam (importing 27% of waste metal), have accelerated urbanization in recent years (Arfanuzzaman and Dahiya, 2019; Behera and Dash, 2017). These countries require large amounts of metals for urban infrastructure and building construction (Reddiar and Osti, 2022). Moreover, the prices of raw metals have been increasing in recent years. Some reports showed that the demand for waste metals is increasing in Southeast Asian countries, driven by construction demand and raw material prices (Choo and Ong, 2019).

However, many waste recycling sites in some Southeast Asian countries are not formalized due to their weak environmental awareness and monitoring methods. Some regions even neglect their local capacity to recycle waste in pursuit of short-term economic gains. This has resulted in large amounts of recyclable waste being piled up locally, landfilled, or illegally dumped (Hu et al., 2021). This is not only detrimental to the recycling of resources but also contradicts Australia's original intention of exporting waste to protect the environment (Table 5).

5.2. Factors related to waste paper

The paper export waste model fit was 0.634. Among all factors, only the local labor intensity (X5) had a highly significant effect ($p<0.01$) on the amount of waste paper exported. The level of local manufacturing development (X3) and employment rate (X7) significantly affect the amount of waste paper. The coefficients of these 3 indicators are positive. This finding suggests that waste paper prefers to be exported to countries with good manufacturing development and high labor intensity. This study uses the level of industrial development and labor to reflect the recycling capacity of the waste import area. Therefore, it is found that Australia's waste paper is more likely to be shipped to countries with higher recycling capacity.

Paper is a waste with less environmental impact. During recycling, shredding and blending paper is the main energy-consuming process. High levels of industrial development in paper importing countries indicate that these countries are more likely to have advanced recycling facilities. For waste paper, these countries are more likely to have the capability to turn it into high economic value products through sophisticated processing rather than simply burning the paper (energy recovery). This is more conducive to the sustainable use of resources.

However, across all indicators, there was no significant relationship between the energy consumed to recycle paper (X6) and the amount of waste paper exported. This suggests that the environmental impact of the recycling process is not taken full consideration when exporting paper waste (Table 6).

5.3. Factors related to waste plastic

The recycling process of waste plastics consumes a lot of energy and is very complicated. As a result, many countries have enacted laws restricting the import of waste plastics. Most of existing studies argued

Table 4
Selected factors.

	Indicator meaning	Reference
X1	The difference in GDP between importing and exporting countries	(Greco et al., 2015)
X2	PPP of importing countries	(Richter et al., 2018)
X3	Manufacturing value added in waste-receiving countries	(Cheung and Pachisia, 2015)
X4	The unemployment rate	(Cavdar et al., 2016)
X5	Labor intensity	(Greco et al., 2015)
X6*	Carbon emissions per unit of recycling in waste-receiving countries	(Sun and Tabata, 2021)
X7	The employment rate	(Greco et al., 2015)

*X6 calculations take into account transportation carbon emissions, recycling carbon emissions, and landfill carbon emissions.

Table 5
The influence of different factors on the amount of waste metal exported.

Model	Unstandardized Coefficients B	Std. err	Standardized Coefficients Beta	t	Sig.
Constant	-70,691	28,698		-2.463	0.019
X1	-13.271	2.547	-1.078	-5.210	<0.001***
X2	0.394	1.135	0.067	-0.347	0.731
X3	-1255	2696	-0.422	-4.657	<0.001***
X4	4794	1241	0.537	3.862	<0.001***
X5	0.005	0.001	-0.354	-3.863	<0.001***
X6	85.3	94.13	0.093	-2.175	0.037**
X7	7851	2725	0.416	2.880	0.007***
R Square	0.792				

**** <0.001,**<0.05,*<0.01.

Table 6
The influence of different indicators on the quantity of waste paper exported.

Model	Unstandardized Coefficients B	Std.err	Standardized Coefficients Beta	t	Sig.
Constant	-45,169	15,947		-2.832	0.007
X1	-2.000	1.578	-0.388	-1.267	0.213
X2	0.371	0.708	0.154	-0.523	0.604
X3	4608	2271	0.243	2.029	0.050**
X4	814.5	4818	0.19	0.169	0.867
X5	0.005	0.003	-5.98	5.023	<0.001***
X6	-0.001	0.909	0.001	-0.003	0.998
X7	4182	1540	0.324	2.715	0.010**
R Square	0.634				

**** <0.001,**<0.05,*<0.01.

that the policy would strongly influence the location of plastic waste exports (Huang et al., 2020). However, the waste plastics analyzed in this study were preliminarily processed. National policies do not currently restrict this type of plastic. Therefore, the waste plastics in this study would not be directly affected by the policies of the importing countries.

The fit of the model was very low for waste plastics exporting. The confidence level of the model was only 0.347. None of the selected factors significantly affected the amount of plastic exported ($p<0.05$). Only one factor, the unemployment rate in the recipient country (X4), may ($p<0.1$) affect the amount of plastic exports. As the coefficient of this factor is negative, Australia's waste plastics have been exported more to countries with lower local unemployment rates.

Therefore, this study can conclude that common social and economic indicators (e.g., GDP, PPP, labor intensity, etc.) have a limited impact on Australia's waste plastics exports. This differs from the findings of other studies. Many studies found that developed countries are more likely to export waste plastics to countries with lower levels of development and poorer economic conditions (Gündoğdu and Walker, 2021).

In addition, some studies suggested that the recycling price may influence the export location of waste plastics (Kumamaru and Takeuchi, 2021). Due to data limitations, import prices of waste plastics were not analyzed in this study. This warrants further investigation (Table 7).

5.4. Factors related to waste tyres

Waste tire is very strictly regulated in many countries. The model has a confidence level of 0.635. Among all factors, the level of manufacturing development in the recipient country (X3) has a significant effect on the amount of tyres exported ($p<0.05$). As the coefficient of this factor is negative, the less developed the local industry of the importing country, the more likely it is to import more tyres. After reviewing the literature, this study found that this phenomenon may be related to the recycling process of tyres (Dobrotă et al., 2020; Sathiskumar and Karthikeyan, 2019; Valentini and Pegoretti, 2022). The current mainstream tire recycling methods require less machinery, equipment, and procedures (Sathiskumar and Karthikeyan, 2019). Meanwhile, tires are charged a high recycling fee (Martínez, 2021). Therefore, some countries have developed recycling waste tyres as an industry. However, using rudimentary processes (e.g., turning tyres into rubber pellets) to recycle tyres does not maximize the value of scrap rubber. This significantly impedes the full reuse of the source.

Except for the level of local manufacturing development (X3), factors related to economic development (X1, X2) may ($p<0.1$) affect the amount of waste tyres negatively. This indicates that countries with greater differences in economic development with Australia import more waste tyres. This phenomenon is consistent with the pollution transfer phenomenon in the literature (Liu et al., 2018). Besides, the coefficient representing the energy consumption of the recycling process (X6) is positive. This shows that Australian waste tyres are more likely to be exported to countries further away and have higher energy consumption in the recycling process (Table 8).

5.5. Factors related to waste glass

In the model fit of this study, the glass model has the highest confidence level, which is 0.98. This means that the indicators chosen for this study significantly impact the amount of glass exported. Among all the indicators, the energy consumption of the recycling process (X6) has a strongly significant effect on the amount of glass exported ($p<0.01$). However, since the coefficient of this indicator is positive, this indicates that more glass goes to areas where the recycling process is less clean.

Besides, the level of industrial development (X3) and labor intensity (X5) of importing countries have a significant effect ($p<0.05$) on the amount of waste glass exported. The level of industrial development (X3) has a positive coefficient among these two indicators. This suggests that Australian waste glass is more likely to be exported to industrially developed regions. This study found that this phenomenon may be related to waste glass production. As waste glass can be processed into various products (Ferdous et al., 2021). The higher level of manufacturing development means that waste glass is more likely to be turned into complex products during processing. This could help the receiving countries of waste glass to gain greater business and also help to enhance the effective recycling of glass.

The coefficient of labor intensity (X5) is negative. This suggests that Australian waste glass is more likely to be exported to regions with low labor levels. This is different from the conclusions of many studies. Many researchers found that waste glass is more likely to flow to regions with high labor levels (Mueller et al., 2012). After reviewing the literature, this study found that this phenomenon can be explained by the recycling process of waste glass (Benzerga et al., 2015; Mohajerani et al., 2017). The recycling process of waste glass is complex. Different colors of waste glass have different recycling requirements (Ling et al., 2013). Therefore, before recycling waste glass, it must be manually screened for color. This makes the recycling of waste glass labor dependent on the

Table 7
The influence of different indicators on the quantity of waste plastic exported.

Model	Unstandardized Coefficients B	Std.err	Standardized Coefficients Beta	t	Sig.
Constant	-920.45	1262.0		-0.729	0.475
X1	0.001	0.006	0.025	0.102	0.920
X2	0.010	0.006	1.121	1.618	0.123
X3	-22.32	23.56	-0.454	-0.948	0.356
X4	-73.23	39.88	-1.435	-1.836	0.083
X5	0.004	0.000	0.475	1.061	0.303
X6	0.671	1.261	0.153	1.596	0.128
X7	7.500	9.835	0.211	0.763	0.456
R Square	0.347				

**** <0.001,**<0.05,*<0.01.

Table 8
The influence of different indicators on the amount of waste tyres exported.

Model	Unstandardized Coefficients B	Std.err	Standardized Coefficients Beta	t	Sig.
Constant	74,986	21,048		3.563	0.001
X1	-0.413	0.234	-0.689	-1.769	0.085*
X2	0.192	0.113	0.658	1.704	0.096*
X3	-646.2	275.5	-0.300	-2.345	0.024**
X4	-564.0	428.3	-0.157	-1.317	0.196
X5	0.001	0.000	0.217	1.579	0.135
X6	0.023	0.028	0.089	-1.149	0.258
X7	-1102	191.3	-0.651	-1.265	0.170
R Square	0.635				

**** <0.001,**<0.05,*<0.01.

preliminary process. However, Australia already does sorting by color before exporting waste glass. Thus, countries that import waste glass can process it directly without requiring manual sorting. This reduces the labor requirements of glass recycling companies, and areas with lower labor levels can also complete waste glass recycling (Table 9).

6. Discussion

At present, Australia's annual waste exports are still on the rise. Taking into account Australia's domestic waste recycling capacity and related policies, this study reveals that Australia is not likely to be able to recycle all of its waste in the short term (Department of the Environment and Energy., 2018, 2020). In the future, it is expected that a certain proportion of waste will still be shipped out of Australia for recycling.

Indeed, transnational recycling of waste cannot be avoided in the short term. Therefore, to target resource recovery and enhance environmental protection, it is necessary to pay attention to the post-export situation of waste. After reviewing relevant literature on the recycling of outbound waste receiving countries ((Chen et al., 2021); Kurniawan et al., 2022; Neo et al., 2021; Panchal et al., 2021; Wang et al., 2019), this study found that inconsistent with most waste exported statistical data, Australia's exported waste is not 100% recycled by waste importing countries. For instance, some imported waste plastics were illegally landfilled in India (ReadOn, 2023). Some reports found there is the same problem in Thailand and Philippines (Campbell, 2022; Greenpeace, 2020). Waste that is not recycled is usually disposed of in landfills in the importing countries. Some studies have found that the unit carbon emission of landfill waste is 5–10 times that of recycling (Ohno et al., 2021). Therefore, the environmental impact calculated on the basis that all exported waste is recycled may largely underestimate the actual impacts. In systems where waste is recycled transboundary, a large fraction of carbon emissions (landfill carbon emissions) is overlooked. However, for now, there are no reliable statistics on the percentage of waste that is recycled, and the products recycled after export. The lack of such data affects the accuracy when analysing the waste recovery systems. This is detrimental to managing transnational waste in different countries and protecting the environment of waste-importing countries. Based on this, this study recommends that waste exporting and importing countries work together to establish a statistical database about transnational recycled waste. This database will allow tracking the final destination of waste (e.g. recycling or landfill). This will be beneficial for waste export-related research. Meanwhile, it provides a useful reference for waste-exporting countries to make decisions when selecting destinations of their exported waste in the future.Besides, this study attempts to analyze the factors that may influence the destination of waste exports. Firstly, the influence of the geographical type factors on the location of exports was analyzed. This study found no significant correlation between the amount of waste exported from Australia and the distance of exported waste. This is inconsistent with the findings of some studies (Sun and Tabata, 2021).

Table 9
The influence of different indicators on the quantity of waste glass exported.

Model	Unstandardized Coefficients B	Unstandardized Coefficients Std.err	Standardized Coefficients Beta	t	Sig.
Constant	-5678.4	3855.6		-1.473	0.154
X1	0.007	0.044	0.031	0.158	0.876
X2	-0.008	0.018	-0.072	-0.414	0.683
X3	112.34	45.323	0.121	2.479	0.021**
X4	320.49	177.08	0.097	1.810	0.083
X5	-0.0003	0.000	-0.127	-3.061	0.006**
X6	0.0009	0.000	0.988	25.549	<0.001***
X7	50.562	26.839	0.100	1.884	0.072
R Square	0.978				

**** <0.001,**<0.05,*<0.01.

The process of transporting waste generates a large amount of carbon emissions from shipping. Therefore, this study suggests that waste exporting countries such as Australia take more consideration of transportation routes when exporting waste.

Apart from the geographical factors, economic, social, and environmental factors were also analyzed in this study. In terms of economic factors, the relationship between the amount of some types of waste exported and economic factors was not significant. However, in general, similar to other studies, Australian waste is exported more to countries with lower levels of economic development. This may be because, in these countries, recycling waste is seen as an industry. By processing the waste, these countries can sell or re-export it as a product. However, after reviewing different reports, this study found that recycling enterprises in many waste importing countries are informal (Greenpeace, 2020) Many residents recycle and process waste (especially plastic) in the form of small family workshops (Dell, 2020; Katz, 2019; OECD, 2022). This recycling workshop is hard to be regulated and may cause some environmental problems due to irregular operations. Some recycling workshops even, to save cost, illegally landfilled the imported waste. Therefore, it is recommended that when exporting waste, waste-exporting countries such as Australia assess the recycling capacity and methods of importing countries to select exporting destinations.

Unlike economic factors, social factors (e.g. employment rate, unemployment rate, labor force level) have different effects on different types of waste. This study found that social factors influence the choice of waste destination, mainly related to the recycling process of the waste. Wastes with simple recycling processes (e.g., tyres, scrap metals) are more likely to be collected by countries with low levels of industrial development but high labor intensity. A higher level of labor means that much waste can be processed in this country and has lower labor costs. Therefore, in such countries, processing such wastes with simple recycling processes is seen as an industry. Recycling large quantities of such waste helps to boost local employment and economic development. However, simple recycling processes also mean that resources cannot be fully utilized. For example, waste tyres can be turned into rubber pellets simply by shredding. But such rubber granules can only be used in paving, not as a material added to high-end products. Therefore, saving costs while enhancing resource use is crucial for future recycling-related research.

Unlike tyres and waste metals, glass and paper are two types of waste that are more likely to be transported to countries with high levels of industrial development for recycling. This is arguably because these two wastes do not rely on a large amount of labor in the recycling process (the labor-intensive sorting has been undertaken in Australia). In addition, these two types of waste can be processed further into high-value products. Countries with a higher level of industrial development are more likely to perform complex processing of these wastes to reap greater economic benefits.

This study also considered the influence of environmental factors on the exporting location. Results show that for some wastes the relationship between the quantity exported and the environmental impact was negative and for some waste was not significant. Overall, Australian waste is not transported to areas with cleaner recycling methods, and the recycling process for most waste remains detrimental to the local environment. To promote sustainable development of resource recycling ecosystems, this study recommends that waste exporting countries, such as Australia, pay more attention to the environmental impacts of transnational waste recycling systems. Waste exporting countries can work together with waste importing countries to facilitate the protection of the environment throughout the region.

7. Conclusions

This study uses the Australian export waste data, combined with geographic information analysis methods, to analyze transnational recycling of waste from the perspective of waste-exporting countries innovatively. Using Australia as an example, the destinations of exported waste were examined. Meanwhile, using regression models, factors that may influence the destination of waste exports are explored.

The results show that, inconsistent with statistics from waste-exporting country, not all exported waste is recycled by the importing-countries. Some of the waste is landfilled in the waste importing-countries instead. This phenomenon could lead to inaccuracy when calculating the environmental impacts of waste recycling transnationally. Therefore, the study recommends that the statistics on the destination of imported/exported waste need be enhanced in the future. In terms of influencing factors, this study found that Australia's choice of destination for exported waste is strongly correlated with importing countries' local economic and social development. Besides, the destination is influenced by the type of waste exported. However, there is no statistically significant correlation between geographic, environmental type factors and destinations. However, these two factors have significant impacts on energy consumption and the environment. Therefore, the study suggests that in the future, waste-exporting countries need to strengthen the consideration of environmental-related factors when exporting waste. The methodology developed in this study (e.g. space center of gravity transfer curve and spatial divergence correlation) has potential to be applied in other contexts to investigate the corresponding transnational waste recycling issues.

There are some limitations associated with this study. Due to data limitations, this study did not consider the source, composition and dirtiness of waste and the recycling prices in importing regions. Future research could be undertaken to incorporate this factor in the model, once the data is made available.

CRediT authorship contribution statement

Linwei Du: Conceptualization, Methodology, Data curation, Investigation, Writing – original draft. **Jian Zuo:** Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. **Kyle O'Farrell:** Data curation, Writing – review & editing. **Ruidong Chang:** Supervision, Writing – review & editing. **George Zillante:** Supervision, Writing – review & editing. **Liancheng Li:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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