The Weight of Islands

A GIS-based material stock analysis of Grenada in the context of extreme weather and climate change

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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ABSTRACT

The building stock consumes large amounts of resources for maintenance and expansion, which is only exacerbated by disaster events where large-scale reconstruction must occur quickly. Recent research has shown the potential for application of material stock (MS) accounts for informing disaster risk planning. This research presents a methodological approach to analyze the vulnerability of the material stock in buildings to extreme weather events and sea-level rise (SLR) due to climate change. The main island of the Grenada, a Small Island Developing State (SIDS) in the Caribbean region, was used as a case study. A stock-driven approach based on a geographic information system (GIS) is used to calculate total MS of aggregate, timber, concrete and steel in buildings. The total MS in buildings in 2014 is calculated to be 11.9 Mt. equalling 112 tonnes per capita given that year's population. Material Gross Addition to Stock (GAS) between 1993 to 2009 was 6.8 Mt and the average value over this time period is 4.0 tonnes/capita/year. In the year following Hurricane Ivan (2004) the per capita GAS for timber increased by 172%, while for other metals, GAS spiked by 103% (compared to average growth rates of 11% and 8%, respectively, between 1993 and 2009). A future hurricane "Ivan-II" scenario to hit the 2014 building stock was also developed and estimated a hypothetical loss between 135 kt and 216 kt of timber stock. The potential impact of sea level rise (SLR) is also assessed, with an estimated 1.6 Mt of building material stock exposed under a 2-meter scenario. Further, I argue that spatial material stock accounts have an important application in planning for resilience and provide indication of the link between natural disaster recovery and resource use patterns.

Keywords**:** SIDS, Grenada, MFA, GIS, construction materials, natural disasters

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1 Introduction

1.1 Resources and Sustainability

In light of the United Nations' 2030 Agenda for Sustainable Development, a central focus in making progress toward the Sustainable Development Goals (SDGs) (UNDP 2016b) is the fact that present-day socioeconomic growth continues to rely on natural resources (Matthews et al. 2000). While many of the SDGs are inherently connected to the coupling of growth and consumption, some are directly relevant – such as #8: Decent Work and Economic Growth; #9: Industry, Innovation and Infrastructure; and #12: Responsible Production and Consumption. In addition to the problem of resource scarcity are the countless environmental impacts stemming from current production and consumption patterns, pushing anthropogenic activity beyond several "planetary boundaries" (Steffen et al. 2015). There is an urgent need for solutions to slow the material throughput of economies without hindering socioeconomic development; this is the concept of *resource decoupling* (UNEP 2011). Similarly, *impact decoupling* is described as decreasing environmental impacts relative to economic growth (UNEP 2011).

Based on a stock and flow principle, the field of industrial ecology quantifies resource use and resource efficiency across socio-economic systems and scale. Scholars of industrial ecology aim to advance decoupling through higher resource productivity and reduced industrial impact on the environment (Ayres, 1996; Ehrenfeld & Gertler, 1997; Fischer-Kowalski & Huttler, 1999). Material and Energy Flows Analysis (MEFA) is the accounting framework for operationalizing society's pressure on the environment through a number of derived indicators. MEFA studies have provided a great deal of insights in understanding long term trends in national and global resource use (Schandl et al. 2016), and how might we move away from linear to closed-loop material flows, also called "industrial symbiosis" (where wastes and byproducts from one process are inputs to another) to aim at higher resource productivity and efficiency (Chertow and Ehrenfeld 2012). Despite improvements in technologies, MEFA studies have shown that global material extraction has tripled and exports have quadrupled since the 1970s while per capita material consumption has nearly doubled (Schandl et al. 2016). A major driver of these trends is the continuing accumulation of resources that remain in-use for extended periods of time:

material stocks. Between 1900 and 2010, the global material stock increased 23-fold, using over half of annual resource extraction (Krausmann et al. 2017).

Material stocks are defined as the materials that remain in socioeconomic use for a year or longer: while this research focuses on the built environment (i.e., construction materials in-use in buildings and infrastructure), the definition of material stocks certainly also extends to other biophysical stocks including durable goods, and human and livestock populations. While analysis of material flows is crucial for monitoring resource decoupling and potential for circular economies, the amount of material stocks accumulated by a society determines current and future flows, and thus is also an indicator of sustainability. In other words, society's sustainability is dependent on the system's ability to reproduce its material stocks by organizing material and energy flows (Wiedenhofer et al. 2016), and it is important to also recognize that material stocks are in place to provide socioeconomic services (Pauliuk & Müller, 2014). Both the quality and quantity of stocks determine the flows required to reproduce them either through domestic extraction or through reliance on trade (Fischer-Kowalski & Haberl, 2007). This complex interrelationship between stocks, flows and services is known as the material stock-flow-service nexus and is of key importance to providing insight on the potential of resource decoupling for sustainability.

This thesis aims to explore material stocks and flows under a special context: the impacts of natural disasters and climate change on the nation of Grenada, a Small Island Developing State (SIDS) in the Caribbean region. Natural disasters are becoming more frequent and costly (UNISDR 2015; Guha-Sapir et al. 2016). SIDS are some of the most climate-vulnerable nations exposed to the intensity and frequency of natural disasters, which cause disproportionately high economic, social and environmental impacts. In the past 40 years, the Caribbean region alone experienced more than 250 natural disasters. Over 12 million people have been affected, with economic damages of about 1% of the Caribbean GDP every year (Acevedo Mejia 2014). The 2017 Atlantic hurricane season alone is estimated to have cost over $200 billion USD in damages (NWS 2017), with storms Harvey, Irma and Maria gaining widespread news coverage as buildings and critical infrastructure stocks were rendered unusable in the US and Caribbean.

Buildings and infrastructure losses result in immediate loss of critical services and the accumulation of a large stock of debris (García-Torres, Kahhat, & Santa-Cruz 2017; Tanikawa, Managi, & Lwin 2014). Restoring the services provided by these stocks comes with large material requirements for reconstruction. These resource flows have massive environmental impacts. Aside from dealing with overwhelming logistical challenges and increasing debts, SIDS rely heavily on costly imports of construction materials to meet demand. Further, due to complex and often hidden dependencies between the functioning and replacement of different types of stocks, recovery is often completed at a delayed rate (Bristow and Hay 2017).

1.2 Research Objectives

This is the first study to undertake a material stock account in the Caribbean region, and to examine the influence of extreme weather events and climate change from a stock-flow perspective. It presents a unique methodology for producing a detailed geospatial database of material stocks in a developing country, and may be applicable to other case studies with similar data-related challenges. Three main questions guided this research:

1) What, and where, are the concentrations of material stocks in Grenada?
2) What are the quantity and quality of construction materials added to stock in Grenada from a flows perspective?
3) How are stocks and flows influenced by extreme weather and climate change?

Three main objectives were identified to answer these questions:

1) Map and quantify the current construction material stock in Grenada's buildings;
2) Conduct a material flow analysis of construction materials, calculating the historical gross addition to stock;
3) Based on these results, construct future scenarios of stock losses due to hurricanes and sea-level rise.

1.3 Study Area

The political boundary of Grenada includes three islands: the main island of Grenada, and two smaller islands, Carriacou and Petite Martinique. Grenada has a population of 106,825 (The World Bank 2017), and an area of 344 sq. km, which translates into a high population density of

310 persons per sq. km. The largest contribution to the economy comes from the tertiary sector, making up over 76% of GDP (The World Bank 2017). Within the tertiary sector, travel services are the largest earner of foreign money, generating a 74% share of Grenada's service exports (The World Bank, 2017). Grenada's economy is also reliant on commodity exports of agriculture products, a sector accounting for 8.9% of GDP (The World Bank 2017), and a small manufacturing industry (Central Intelligence Agency 2017). The World Travel & Tourism Council (2018) estimates travel and tourism is responsible for 23.3% of GDP, and 21.4% of employment in Grenada. Material stocks are highly important to the tourism industry in the form of accommodations and infrastructure, and growth of the tourism industry requires expansion and maintenance of stocks in order to accommodate more tourists. Due to the seasonality of the tourism industry in Grenada, irregular influxes of tourist populations stress island infrastructure during peak seasons while leaving stocks unproductive and idle during off seasons. This seasonality of stock use was observed in Samothraki, Greece (Petridis and Fischer-Kowalski 2016). Grenada has a high coastline-to-land-area ratio of 733 m/km^2 (Central Intelligence Agency 2017), and is a mountainous island. Despite this, material stocks supporting socioeconomic activity are situated in vulnerable low-lying coastal locations (Parry 2007) exposed to sea-level rise due to climate change, with 1 to 2 meter increase above present sea levels likely by the year 2100 (Simpson et al. 2010) and a potentially more severe situation as sea levels continue to rise during the 22nd century.

Extreme weather is another major concern: In 2004, Hurricane Ivan damaged 89% of homes in Grenada, with 30% completely destroyed (The World Bank 2005). The hurricane also impacted social services infrastructure, as the majority of public health and education buildings were severely damaged. Within the tourist industry, 70% of hotel infrastructure was unusable (The World Bank 2005). In a context of already scarce and unsecure resources, the material flows required to reproduce material stock undoubtedly put large pressures on the island socioeconomic system, both from inputs needed for rebuilding/restoration and output of unusable damaged materials.

1.4 Thesis Structure

This thesis begins with a Literature Review (Section 2) describing the theoretical background of socioeconomic metabolism and material stocks, followed by a review of the state of the art of material stocks research and key empirical findings and ending with a review of vulnerability of islands. Section 3 describes in the detail the development of the methodology used to model material stocks in Grenada's buildings and the scenarios for impacts due to extreme weather and sea-level rise, and also includes the material flow analysis methodology used to estimate construction materials added to stock in time series. The results from these methodologies are then presented in Section 4, followed by discussion and conclusions of the key results in Section 5.

2 Literature Review

2.1 Socioeconomic metabolism

Long-term socio-ecological research aims to combine knowledge from longitudinal monitoring, historical data, modelling and forecasting to inform sustainable management of socioeconomic activity (Singh et al. 2013). It is rooted in a systems approach that focuses on the coupling of human activities with nature; that is, a theoretical framework for studying society-nature interactions. This epistemology bridges the social and natural sciences, viewing humans and their artifacts at the intersection of spheres of natural and cultural causation (Fischer-Kowalski and Weisz 1999). Acknowledging the interdependencies of cultural and biophysical systems, this framework aims to track the relationship between socio-economic activities and ecosystems in biophysical terms (Haberl et al. 2004). The exchange of material and energy between the natural world and society's biophysical stocks is known as socioeconomic metabolism. Metabolism was conceived in the natural sciences to describe the biochemical processes that sustain life, but similarities in fundamental properties of biological and socio-ecological systems make it a transferrable concept (Marina Fischer-Kowalski 1998; Marina Fischer-Kowalski and Weisz 1999). Socioeconomic metabolism is operationalized by industrial ecologists using the material and energy flow analysis (MEFA) accounting framework. It is a comprehensive accounting system for social metabolism that ensures consistency across time and space (Haberl et al. 2013). This is important for two reasons: i) the socio-ecological framework integrates across different scales, so metabolism of 'sub-compartments' must be additive to metabolism of the whole system (Fischer-Kowalski and Weisz 1999); and ii) in the case of studying long-term trends, the framework is compatible across time as social systems change (Haberl et al. 2013).

Socioeconomic stock, and the metabolism associated with its maintenance and expansion, is a key component of the MFA framework. The scope of this framework, shown in Figure 1, includes quantified inputs from domestic extraction and external socioeconomic systems, and outputs as waste emissions or exports to external socioeconomic systems.

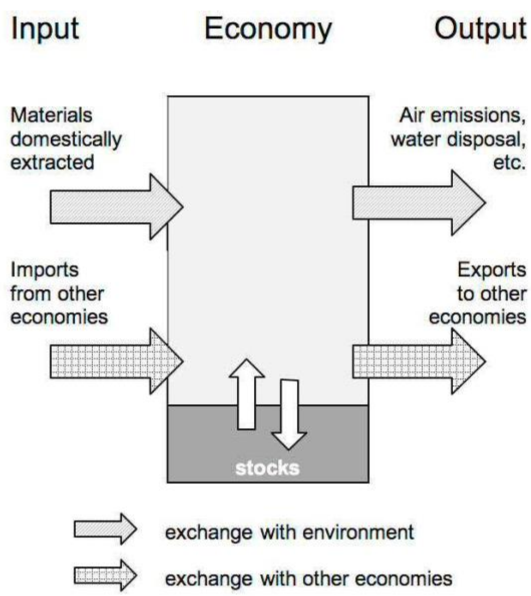


Figure 1: The material flow analysis (MFA) framework (Krausmann et al. 2015).

2.2 The Material Stock – Flow – Service Nexus

Socioeconomic metabolism (SEM), much like its biological analogy, must be maintained for the social system to continue to function. More specifically, this metabolism reproduces and maintains the biophysical structures – or stocks – of society. These stocks include humans, livestock, and durable artifacts (built infrastructure and other durable goods). As Fischer-Kowalski & Weisz (1999, p.14) note: "*Ceteris paribus*, the more objects a society needs, owns and seeks to maintain, the larger will be its metabolism". Material stocks couple services to material use (Pauliuk and Müller 2014) and their specific characteristics (quantity and quality) will determine both present and future flows of materials. This interrelation of material stocks, flows and services provided has been coined the **material stock – flow – service nexus**, which is argued by Haberl et al. (2017) as a key approach moving forward in SEM research.

Material flow studies at different scales have been used to evaluate efficiency of resource use for sub-national (for example urban metabolism), national, regional and global scales (UNEP 2016). The benefit of macro-level measurements is to evaluate the level of resource decoupling occurring (Haberl et al. 2004), i.e., increasing resource use efficiency (UNEP 2011). Efficiency is operationalized as "material intensity", a measure of material throughput per dollar of GDP (UNEP 2011). Although a growing body of research indicates that material stocks have not played as prominent a role in SEM research and thus a key component of the material stock-flow-service nexus has not been extensively analysed in most socioeconomic systems. Nonetheless, while efficiency indicators such as Domestic Material Consumption (DMC) per capita and material intensity have been applied to flows, it is clear from the growing body of research on stocks that efficiency must be evaluated in this domain as well. For example, Fishman et al. (2014) apply the material intensity indicator to material stocks (material stock/GDP) in Japan and the US. Alternative to monetary measures, the physical services provided by stocks can be used to monitor efficiency. Lwin et al. (2017) developed a stocked material use efficiency (SMUE) indicator for sewer pipelines, measuring the volume of treated water per mass of pipeline stock.

Due to their role in socioeconomic activity, per-capita stock levels can be expected to rise as society industrializes. Indeed, this is reflected in empirical findings to date (see Section 2.4). Energy- and emission-intensive supply chains supporting the construction and maintenance of built stock must also be considered, as these material flows and their impacts often reach far outside the political jurisdictions of the stock (Reyna and Chester 2015). This is the concept of embedded (or embodied) environmental effects (Reyna and Chester 2015), which accounts for the life-cycle material and energy flows involved in the stocking of a material in its end-use (Hammond and Jones 2008).

The seminal report, *The Weight of Nations* (Matthews 2000) was an MFA of five industrialized nations: Austria, Germany, Japan, The Netherlands, and United States. It presented aggregated, economy-wide indicators for the socioeconomic metabolism. Because the indicators were on an annual timescale, there was a factor to account for material that remained in the economy for longer than one year if the system is mass-balanced: net addition to stock (Matthews, 2000; Pauliuk & Müller, 2014). In discussion of the NAS results, Matthews (2000) highlights the dominance in mass of construction materials and the important role of recycling. Accurately modelling material stock outflows could help identify potential deposits of resources for use in the future (Graedel 2010; Hendriks et al. 2000; Ortlepp, Gruhler, and Schiller 2016). Strategies to decouple services from stocks are imperative to achieve reductions in material throughput (Pauliuk & Müller, 2014) and put socioecological systems on more sustainable pathways (Singh et al. 2013). Understanding and forecasting end-of-life waste flows are important for closed loop resource cycles to benefit resource & impact decoupling by limiting virgin material extraction and can be leveraged for monitoring impact decoupling. Sub-ground-level portions of buildings/infrastructure often become dissipated stock because it remains after demolition, and is of key importance to predict future inflows/outflows (Tanikawa and Hashimoto 2009). Subsurface materials are hard to remove and have potential environmental implications such as heat island and urban climate change effects (Tanikawa and Hashimoto 2009).

Additionally, understanding the input and outputs flows associated with material stocks could help planners and policy makers with precautionary planning as opposed to reactionary measures (Hendriks et al. 2000).This is especially important in scenarios where material flows increase drastically in a short period of time, such as during a disaster event. Forecasting debris and reconstruction flows following hydra-meteorological and geological disasters requires a detailed understanding of the material stock, but has valuable applications for vulnerability and risk assessment (García-Torres et al. 2017).

2.3 State of the art in material stock research

Stock-flow studies of construction materials have been broadly categorized into having 4 main purposes (Augiseau and Barles 2017): forecasting future input/output flows – i.e. forecast consumption and waste; estimating the present stock and various characteristics, such as age, material, spatial distribution; estimating future stock composition; and finally, stock plays a central role in urban metabolism studies. Methodological approaches are often distinguished as either top-down or bottom-up, which are detailed in the following sections. However, a special session on material stock research at the International Society for Industrial Ecology (ISIE) Conference, 2017, featured a discussion on the distinction between top-down and bottom-up approaches; there was not a clear consensus in the field on definition of these terms due to the varying purposes, data availability and data requirements among research in the categories (Special Session: "State of the art and future directions in the study of the built environment's stocks and flows", ISIE-ISSST 2017). Therefore, it is important to emphasize that although these categorizations do group similar methodologies together, they do not represent "harmonized" accounting frameworks like the economy-wide material flow accounting framework (EW-MFA; Eurostat, 2013) used for MFA. Distinctions used in (Augiseau and Barles 2017) such as dynamic vs. static or **flow-driven vs. stock-driven** analysis are more descriptive and communicate which data are exogenous.

2.3.1 Flow-driven approaches

Also known as top-down, flow-driven approaches generally use historical material flow data to determine annual net additions to stock (NAS). The local-scale study of SangSaeng village (Finnveden et al. 2009) used this method, looking at NAS as an aggregate value of all materials' mass. Fishman et al. (2014) used historical material flow data for the United States and Japan to calculate accumulation of stocks from 1930 to 2005. More recently, the top-down MISO model developed by (Krausmann et al. 2017) has used a global MFA database to calculate global material stock. While material inflows are calculated using historical data, outflows from stock need to be modeled based on lifespan characteristics of different buildings and infrastructure (i.e. mean, std. deviation for lifespan of a building/infrastructure type). End-use lifespans can be modelled with normal distributions (such as in Fishman et al. 2014), but Weibull, Log-normal, Gamma and Gompertz distributions have also been used (Miatto, Schandl, and Tanikawa 2017). For example, (Pauliuk, Wang, and Müller 2012) assume that much of steel stocks would remain in construction uses for longer periods than other categories, such as machinery or appliances. To better capture this characteristic, the lifetime distribution for steel in construction was modeled with a Log-normal curve, which is characterized by a tail "stretching out" to older lifetimes; Miatto, Schandl, and Tanikawa (2017) also found this distribution to be most appropriate for buildings in their case studies. Various socioeconomic factors also determine lifespan for a given end use turnover: Lifespan of infrastructure is not only determined by physical condition of the structure, but also by aspects such as location, market prices for land (Tanikawa and Hashimoto 2009); vacancy (Kohler and Hassler 2002); and institutional regimes protecting cultural capital can increase the longevity of different inter-generational buildings and infrastructure (Hassler 2009).

Flow-driven methodologies can integrate much better with MFA (Tanikawa et al. 2015). A top-down approach is limited in application to systems with the necessary historical data, working well for national material stock accounts using aggregate material flow indicators, or industries with reliable raw material data.

2.3.2 Stock-driven approaches

Also commonly referred to as bottom-up approaches, these methods are often called a static analysis because they take an instantaneous measurement of in-use material stock (Tanikawa et al. 2015). This methodology requires taking inventory of materials in end-uses and dividing them into groups or types that share a material intensity (MI), or material composition indicator (MCI). The local-scale study of Trinket Island by Singh et al. (2001) follows this approach: taking a representative sample of different built structure types on the island, determining their MI, and then taking a count of each structure type. Ortlepp, Gruhler, and Schiller (2016) takes the same general approach, where MCIs (e.g., mass per floor space) are used with established building typologies, and the total square footage of each typology is determined from economic data detailing stock of fixed assets. Geographic information systems (GIS) have become an important tool in making stock-driven accounts more feasible on larger scales. For example, material stock accounting of Japan by Tanikawa et al. (2015) used prefecture-level GIS databases to take count of structures (and their floor space) in conjunction with government construction codes as a MI estimator. GIS has also been used for material stock accounts in other studies at a city-wide scale: Tacna (García-Torres et al. 2017; use of GIS allowed for integration with the CAPRA-GIS tool to estimate physical damage based on earthquake event magnitudes) and Chicaylo (Mesta, Kahhat, and Santa-Cruz 2018) in Peru, and Salford, UK and Wakayama, Japan (Tanikawa and Hashimoto 2009).

Stock-driven approaches allow for gaining specificity on quality of material contained in end-uses, and understanding the spatial distribution is often feasible with these methods. Additionally, accurately capturing age of stocks is possible. However, the drawbacks are apparent as well: studies of this type can be very time consuming to undertake. Without the extensive data that a nation such as Japan collects, methods more in line with Singh et al. (2001) are required – for a larger region, this requires extensive time and resources. A key advantage of many stock-driven methods is that they include detail on spatial distribution and socioeconomic end-use, opening different avenues of analysis with respect to interrelations between stock and services. And while thought of as an instantaneous measurement, stock-driven accounts can also be dynamic in nature (Augiseau and Barles 2017); Wiedenhofer et al. (2015) is an example of a dynamic stock-driven account for the EU-25, and more recently (Noll et al. submitted) for Samothraki in Greece. This approach uses time-series data of the extent of stock containers (i.e. multiple "snapshots"), which allowed for a prospective material flow analysis.

2.3.3 Hybrid and alternative approaches

Remote-sensing techniques have been used to estimate material stocks (Tanikawa et al. 2015); for example, light intensity from night-time satellite imagery has been an avenue of study for distribution of copper stocks (Terekado et al. 2009; cited in Tanikawa et al. 2015), and more recently for steel (Liang et al. 2014, 2017).

While stock-driven approaches to material stock accounting can provide good spatial resolution and other material-specific detail, flow-driven approaches provide a more feasible method at large scales and integrate well with the MFA framework used by industrial ecologists. In terms of data requirements, there is a need for better stock characteristics information, i.e. age, composition, lifespan, and material outflows from stock, including demolition activities (Haberl et al. 2016; Wiedenhofer et al. 2015), though Tanikawa et al. (2015) note that the detail provided on in-use age of stocks gained from stock-driven methods can be used to refine the modeling of outputs from stock in flow-driven studies. Additionally, overlapping results present a potential opportunity to calibrate the methods. Moving forward, neither methodology should be considered a best practice, but rather they are perspectives that can be combined (Kohler and

Yang 2007); the hybrid flow-/stock-driven approach used by Schiller et al. (2017) for construction material stock in Germany is a key example of integrating these two approaches.

2.4 Key findings from material stocks research

Between 1900 and 2010, the global material stock has increased 23-fold with 55% of annual resource extraction being added to stock (Krausmann et al. 2017), and the rate of accumulation is accelerating (Fishman, Schandl, and Tanikawa 2016). National-scale studies provide further insight into this growth: from 1930-2005, material stocks in Japan and the United States grew 40-fold and 9-fold, respectively, with both nations experiencing a decrease in timber use while stocking of non-metallic minerals grew (Fishman et al. 2014). Local studies have found (Grünbühel et al. 2003; Singh et al. 2001) material stock growth partly due to modernization of construction materials, suggesting that aside from increasing volume of stocks, the modernization of material composition observed at different scales plays a role in the total mass of natural resources accumulating in the built environment. Additionally, the end-use type is an important factor in material composition, as research has shown non-residential buildings contain more non-metallic minerals and metals than residential buildings (Germany; Ortlepp, Gruhler, and Schiller 2016).

Material stock per-capita is a useful indicator as research emerges at different scales and for varied population sizes. For developed nations with mature economies, high levels of per-capita stocks are expected. Fishman et al. (2014) found per-capita levels of material stock for the US and Japan to be 375 and 310 tonnes respectively, in line with 311 tonnes for Switzerland (Rubi & Jungbluth, 2005; cited in Fishman et al. 2014), and an account by Schiller et al. (2017) estimates Germany's per-capita stock at 347 tonnes, or 340 tonnes for only building materials. This is in contrast to agrarian Trinket Island's material stocks, at 9.1 tonnes per capita (Singh et al. 2001). A recent MS account by Noll et al. (submitted) for the island of Samothraki in Greece found stock to be at similar levels to Japan and the US

Kohler & Hassler (2002) emphasize the importance of the building stock's long-term behaviour, especially the issue of maintenance flows. Similarly a supranational study of the EU-25 by Wiedenhofer et al. (2015) looked at residential buildings and transportation infrastructure; the dynamic stock model presented estimated 34-58% of domestic material consumption (DMC) of construction minerals are used for maintenance of extant stock, while an additional 28% of this material category goes into stock expansion.

Industrial ecology, and stocks research more specifically, has also been applied to hazard vulnerability research. For example: impacts of possible earthquakes on the housing material stock in Tacna, Peru (García-Torres, Kahhat, and Santa-Cruz 2017); and lost material stock of buildings and roads in Japan due to the 2011 earthquake and tsunami (Tanikawa, Managi, and Lwin 2014). Incorporating MFA in the timeframe surrounding a disaster scenario allowed for analysis of the material supply chain/reverse supply chain to identify issues of scarcity or overburden (García-Torres, Kahhat, and Santa-Cruz 2017). In addition to informing disaster risk assessment and prevention, these methodologies also have the added benefit of forecasting waste flows; while useful in any scenario, this forecasting ability could especially relevant for a small island as the pressures and impacts of the stock-flow of waste are felt in close proximity to the rest of the socioeconomic system (Deschenes and Chertow 2004).

2.5 The island context

2.5.1 Vulnerability & resilience

The motivation for studying islands comes from recognition of their vulnerable socioecological systems, and the necessity for more immediate sustainable development solutions than continental nations (Deschenes and Chertow 2004). A vulnerability framework has been developed in the context of socioecological systems by Turner et al. (2003), where a system's vulnerability is comprised of exposure, sensitivity and resilience; that is, vulnerability is a function of both internal and external factors (Turner et al. 2003). In terms of these factors, Small Island Developing States (SIDS) all share similar challenges within the context of climate change. Turvey (2007) developed a composite vulnerability index (CVI) that factored in coastline-to-land area ratio, remoteness, insularity, urbanization and natural disaster exposure; when comparing SIDS' CVI among other developing countries, they were found to be highly vulnerable (especially compared to larger island countries) (Turvey 2007). Some sustainability issues shared among SIDS are: limited scope for economic diversification (UNDP 2016a), scarce natural resources resulting in economic reliance on imports of food and fossil fuels (Chertow et al. 2013; Krausmann et al. 2014), growing tourism sectors, and emigration of skilled and educated populations. This leaves the island socioeconomic system vulnerable to global-scale forces (Deschenes and Chertow 2004). Additionally, exposure effects of climate change increase SIDS' vulnerability due to hazards and worsening of other pressures on socioecological systems (Weir and Pittock 2017). For example: SIDS' on average have 30% of their population residing below 5 meters above sea level (UN-OHRLLS 2013), a concerning situation given the likelihood of a 1- to 2-meter increase in sea levels by the year 2100, and worsening conditions into the 22nd century (Simpson et al., 2010). Exposure to extreme weather is another major concern, with small islands among the most impacted by tropical cyclones (Eckstein et al. 2017). In this respect, progress towards two Sustainable Development Goals are highly salient for SIDS. Firstly, #9: Industry, Innovation and Infrastructure; resilient infrastructure systems are needed in terms of both reducing disaster vulnerability of built works and addressing technological capabilities for risk management. Secondly, #13: Climate Action; a key target for this goal is to strengthen adaptive capacity to climate-related hazards and natural disasters in all countries (UNDP 2016b), but the urgency is highly apparent for SIDS.

Land management and its implications have been studied for SIDS in both the Pacific (Wairiu 2017) and the Caribbean (Mycoo, Griffith-Charles, and Lalloo 2017) regions. The limited space on small islands creates strong competition between different land-uses, and extensive coastal development for tourism competes with housing (UN-OHRLLS 2011). According to Weir & Pittock (2017, p.955): "Unsustainable land management practices have led to degradation becoming an emerging concern in many SIDS in recent years." For example, Mycoo et al. (2017) found land-use planning regulations in St. Lucia (another southeastern Caribbean island) were allowing the expansion of material stocks in an unsustainable and environmentally degrading way. Grenada, the case study in this research, has been the subject of studies on hazard and risk information (Alam 2015; Pratomo 2015).

2.5.2 Island industrial ecology

Islands are excellent focal points for studies of industrial ecology. Not only do the clear boundary of islands simplify tracking resource flows, but the limited resource availability and carrying capacity of islands warrants better tracking and management of these inputs and outputs. As the saying goes: "If you can't manage it, you can't measure it;" industrial ecology provides data and information to planners and policy makers on the physical basis of island economies, that is, on the quantity and quality of material and energy domestically produced, imported, transformed, used, and discarded. Eckelman et al. (2014) argue that industrial ecology tools such as life cycle assessment, MEFA and industrial symbiosis can be applied to better understand waste management issues on islands. Thus, data generated by industrial ecologists can effectively be used to move island societies towards more sustainable modes of production and consumption.

In the context of these socioeconomic vulnerabilities, land-use issues, and natural hazards, the role of material stocks on SIDS has not been studied; however, their influence on an island's metabolism, and characteristics such as technological design and spatial arrangement are important consider in a socioecological system vulnerability framework. Applying the stock and flow principle to islands, island industrial ecologists has produced several social metabolism studies to date: economy-wide material flow accounts have been established for Iceland and Trinidad and Tobago (Krausmann, Richter, and Eisenmenger 2014), the Philippines (Martinico-Perez et al. 2017), Cuba (Eisenhut 2009), and the Caribbean, aggregated with Latin America (West and Schandl 2013); waste and emission patterns have been studied for Hawaii (Houseknecht 2006) and Malta, Spain (Conrad and Cassar 2014); and a study on Jamaica focused on biomass flows (Okoli 2016). Material stocks have been studied on a locale scale for two islands: Trinket, Nicobar Islands (Singh et al. 2001) and Samothraki, Greece (Noll et al. submitted).

For islands relying heavily on tourism, some industrial ecology research has paid special attention to this economic sector; for example: Petit-Boix (2017); Petridis et al. (2013); Petridis & Fischer-Kowalski (2016); Telesford (2014); Telesford & Strachan (2017). Specifically, for stocks and flows related to this sector, the material, energy and waste flows for the Grenadian tourist accommodation sector (Telesford 2014; Telesford & Strachan 2016) were analyzed to guide strategic sustainability procedures for business/enterprise, while Petridis & Fischer-Kowalski (2016) used a socioecological framework to study metabolism on the Greek island Samothraki. A key consideration from these studies was the importance of the supporting infrastructure stock to tourism services; notably, the seasonality of tourism results in fluctuating utilization of infrastructure stock throughout the year (Petridis and Fischer-Kowalski 2016). Research using the life cycle assessment (LCA) methodology has also examined this issue, focusing on wastewater infrastructure for a seasonal settlement on a Spanish island (Petit-Boix 2017). To date, material stocks have not been studied for Grenada or any Caribbean nations.

3 Methodology

3.1 Introduction

This chapter describes the methodology used to address the research objectives. Spatial data for administrative, land-use, topographic and risk information uses were compiled in a geodatabase for Grenada to be readily available for analysis in this thesis and any future work. This geodatabase was used in a classification system to characterize the use-types and construction style of buildings. This detailed building inventory was then used along with a set of material intensities (MIs) to calculate materials stocked in buildings in four aggregated categories. This stock-driven approach is described in detail in Section 3.4, and is followed by a description of the methodology used to assess a future scenario of material stock lost to an extreme weather event (Section 3.5). Finally, Section 3.6 presents the material flow analysis (MFA) methodology used to compile construction material flows and inputs to stock from 1993 to 2009.

3.1.1 System boundary

Analyzing the material stocks and flows of a socioeconomic system requires that an appropriate system boundary is defined. This boundary is defined on both a spatial and temporal scale, and takes into account the socioeconomic system's interface with both the natural environment and other economies (Eurostat, 2013; M. Fischer-Kowalski et al., 2011). Figure 2 provides a visualization of the flows across this system boundary and their association with the in-use material stocks that reside within the system. This study firstly conducts an analysis of a sub-set of in-use material stocks: buildings on the main island of Grenada. The methodology provides an account of four construction materials in-use in the 2014 building stock: aggregate, concrete, wood and steel. This is referred to as a sub-set because other containers of the material stock are not quantified for the following reasons:

1. **Other materials in modern-day buildings (e.g. glass, plastics, ceramics, copper, etc.):** These materials make up a relatively small share of the total material stock; additionally, they also have higher variability from one building to the next so it is harder to find a typical representative value that can serve as the expected material intensity.
2. **Traditional construction styles (e.g. adobe or clay), and other construction styles (e.g. brick):** Adobe or clay structures were not observed to be very prevalent during field work. Looking at the housing census (Central Statistical Office 2011): stone, brick, makeshift and "other" wall materials make up <1% of all homes, which indicated that these were not very prevalent materials in Grenada. Most observed brick structures were in old institutional buildings or were abandoned altogether, so in the context of an economy "reproducing" its stock with future flows, it did not appear that brick was relatively important.
3. **Smaller durable goods (e.g. furniture):** Similar to the first point, this stock has high variability of material quality and quantity, and they have different life cycles than the buildings themselves.
4. **Sheds, shacks, and temporary constructions**: The building inventory dataset contained many small features that were expected sheds, shacks, and vehicles – but differentiating between these items was not possible. So, the dataset was "cleaned" of features < 5 sq m. Additionally, during field work these small structures did not appear to have foundations (i.e. little to no concrete) or any common style of construction, so they were omitted.
5. **Civil infrastructure (e.g. roads, wharves & piers, airstrips, agricultural infrastructure, dams, etc.):** A primary problem was finding inventory data for any civil infrastructure. For the extreme weather scenarios in this study, the interest was the impact on buildings, as other infrastructure types were mostly unaffected by hurricane Ivan in 2004. Nonetheless, investigating the impact of sea-level rise on civil infrastructure it certainly a future direction of study for islands.

The subsequent MFA methodology used for construction material flow compilation is an economy-wide account of Grenada consistent with Eurostat (2013) methodology, and as a result encompasses all three islands of Grenada's political boundary. Additionally, a more comprehensive set of construction materials is considered than in the material stock account for buildings. The temporal extent of the MFA is from 1993 to 2009.

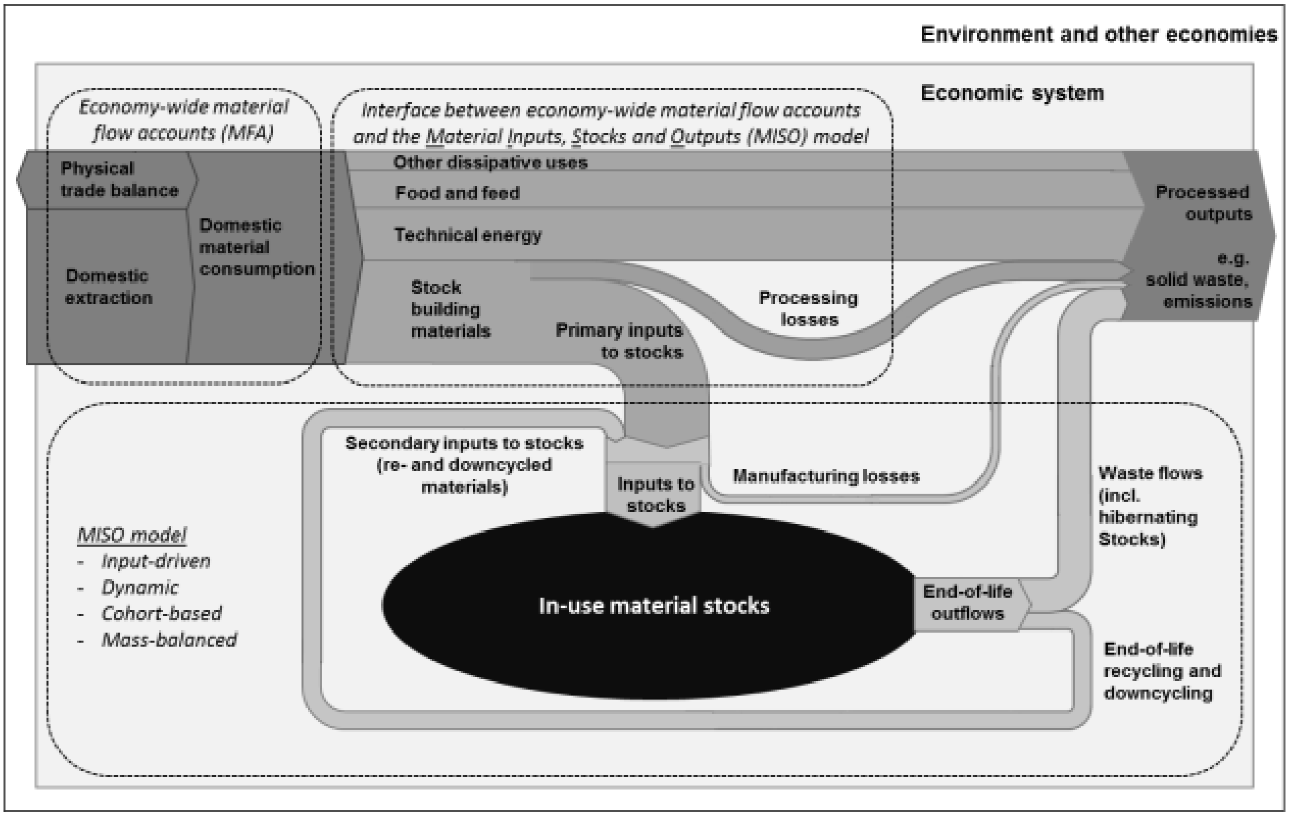


Figure 2: Socioeconomic system boundaries, and the relationship between economy-wide material flows and in-use material stocks (Krausmann et al., 2017).

3.1.2 Field work

Field work in Grenada was conducted for two weeks in September 2017. Meetings were held with local organizations including:

- Physical Planning Unit of the Ministry of Infrastructure Development, Public Utilities, Energy, Transport & Implementation
- Land Use Division of the Ministry of Agriculture & Lands
- Forestry Division of the Ministry of Agriculture & Lands
- Grenada Solid Waste Management Authority
- Officials working in the beach resort industry
- A representative of T.A. Marryshow College, Mirabeau Campus

These meetings were conducted with the goal of filling gaps in data required for the methodologies described in this section. Additionally, the conversations held in an official capacity also provided additional context to help interpret the results of the thesis. Apart from meetings with local partners, a general survey was conducted to learn more about construction of buildings and general spatial planning on the main island of Grenada. 485 photographs were taken to help inform the methodology development for material stock analysis during the Winter 2018. The camera used had GPS capabilities, which allowed for identifying the location of each photograph.

3.2 Methodology for material stock analysis of buildings

This section describes the steps taken to quantify and map the materials in-use in Grenada's buildings. The methodology can be classified as stock-driven (Augiseau and Barles 2017; Tanikawa et al. 2015). As discussed in Section 2.3.2, this approach involves categorizing the building inventory into different typologies and applying material intensities to calculate the total material stock. The steps taken to characterize the building inventory and sort it into a set of typologies is first described, followed by a derivation of material intensities Finally, the calculation of material stocks is described.

3.2.1 Creating a geodatabase for Grenada

During preliminary data collection, several sources were found on topics ranging between administrative, land-use, topographic and risk information. Before undergoing any analysis, the data was imported into a geodatabase[1] in ArcGIS, where quality-checks and data-cleaning could be performed. For example, spelling and formatting errors were corrected to ensure consistency across the different datasets being imported. Additionally, a metadata catalog was maintained for all items in the geodatabase to document details including the source, description, data type, resolution, units, and temporal extent. The metadata for the geodatabase is included in Appendix A.

3.2.1.1 Data sources

The sources for the geodatabase and the general topics they cover are outlined in Table 1. A key dataset for this research methodology was the Grenada building footprints Shapefile from the

[1] A geodatabase is a collection of datasets, that among other attributes, contain geographic information for the data points. The datasets in a geodatabase are related to each other because they are defined in a defined geometric space using a geographic information system (GIS) such as ArcGIS.

Caribbean Handbook on Risk Information Management (CHARIM) project, which is discussed further in the following section.

Table 1: Summary of data sources for the geodatabase for Grenada.

Source	**Topics**
Caribbean Handbook on Risk Information Management (CHARIM)	Administrative, demographic, land-use, buildings, topographic, risk information
The World Bank	Impacts of Hurricane Ivan (2004)
Field Work	Photographs of buildings
Grenada National Census	Demographic, housing construction styles
Grenada Dept. of Agriculture	Land-use data
OpenStreetMap	Building footprints, roads

3.2.2 Characterization of building footprints

The first step taken was to develop a system to classify buildings in Grenada. The classifications would be used to estimate building heights and material composition for the 2014 footprints based on a 'composite' analysis using layers in the geodatabase. Height estimates would allow for calculating gross floor area (GFA) for Grenada's building stock, and combined with material intensity estimates, the total stock of in-use construction materials in buildings could be calculated. This step would also provide important information about building use-types and services provided.

3.2.2.1 Occupancy classification system

The goal of the classification system was to define a set of representative "occupancy classes" that the building footprints could be grouped into (see Table 4). These occupancy classes describe the specific use-type of the building (e.g. Rural-area single-family dwelling), and were to be differentiated to a level to which the following conditions and assumptions were met:

i. Each footprint in an occupancy class was expected to have the same building height (i.e. number of floors)
ii. For non-residential buildings: the occupancy class shared a construction style (i.e. each footprint would be assigned the same material intensity)
iii. For residential buildings: the construction styles in the occupancy class could be allocated by percentages of all dwellings given in the 2011 National Census

The primary challenge at this stage was to ensure it would be possible to differentiate between these classes from a geomatics and image interpretation perspective, and that a mostly automated approach to classification could be taken (as there were over 58,000 footprints). To ensure feasibility a "trial run" was conducted. The trial run involved selecting one building footprint example for each of the typology classes and working through a composite image interpretation approach for each. Image interpretation is a popular technique to identify classes of buildings (Du et al. 2014). For each typology class, a screenshot of a building footprint example was shown along with satellite imagery, spatial association info, Google Earth satellite imagery, OpenStreetMap layers, and field work photos if available. An example set of images is shown in Figure 3, and the full collection of samples can be found in Appendix B. This provided an example of each occupancy class and tested feasibility of using the geomatics/image interpretation perspective to inform assumptions about occupancy, building height and construction style.

The 2014 building footprints from CHARIM already had some classification (Alam 2015) into several different use-types through visual interpretation of satellite imagery, field work and

Figure 3: Sample of a composite image interpretation of an occupancy class.

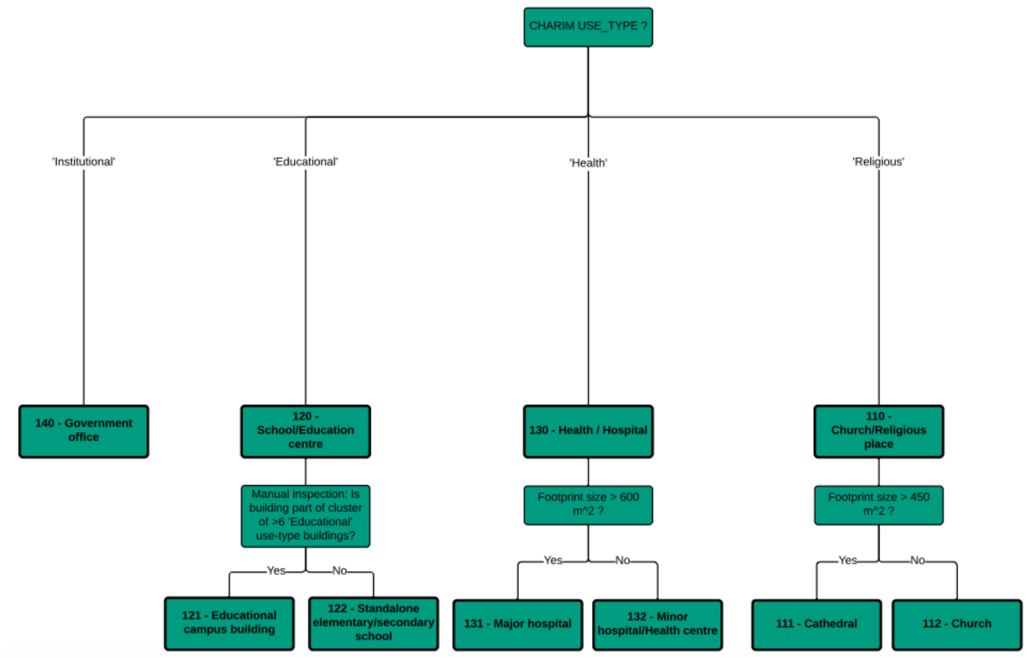
expert consultation; these use-type data were the first criteria in the classification system developed here. Information such as footprint size, land-use and location were then used to further differentiate buildings. The criteria used and their sources are shown in Table 2 below. While some criteria were intuitive to use (e.g. spatial association with agriculture land-use could signify a rural home), refining the use of footprint size proved to be difficult and required an iterative process over test areas to achieve the desired results. For example, beach resorts often are large compounds that can have a variety of buildings ranging from small, single-story villas to tall, multi-unit buildings. Figure 4 shows the variation in building heights at Sandals Resort in Grenada. While classifications from Alam (2015) indicated which buildings were part of the resort, it was advantageous to use the footprint size to differentiate between these building types and place them in separate occupancy classes.

Table 2: Criteria from the geodatabase used in the building classification system.

Criteria	**Source**
Building use-type	Alam (2015), CHARIM GeoNode
Building footprint area	2014 building footprints (CHARIM, 2016)
Spatial association with land-use	Grenada Dept. of Agriculture land-use data (2009)
Census enumeration district	Grenada Central Statistical Office (CSO), CHARIM (2016)
Manual inspection for recognition features	Google Satellite Imagery

Figure 4: Photo of Sandals Resort, Grenada illustrating the varying building heights on a resort compound. Photo taken during field work, September 2017.

The final occupancy classification system is presented in Figures 5 through 10 in the form of "decision trees" for six overarching use-types: Institutional, Commercial/Industrial, Residential, Tourism, Cultural, and Transportation. Beside each decision tree, its implementation on a test area in the Town of St George's is shown to illustrate the spatial distribution of various occupancy classes. *Table 4* lists the 25 occupancy classes defined in the system. While some occupancy classes are only coded to the 2nd-digit level (e.g. 210, 220, 230), others are coded to the 3rd-digit level (e.g. 411, 412, 413). This reflects the iterative process of developing the classification system; an earlier version had all classes at the 2nd-digit level, however after trial runs certain classes required further differentiation, resulting in 3rd-digit level codes for some classes in the final set.



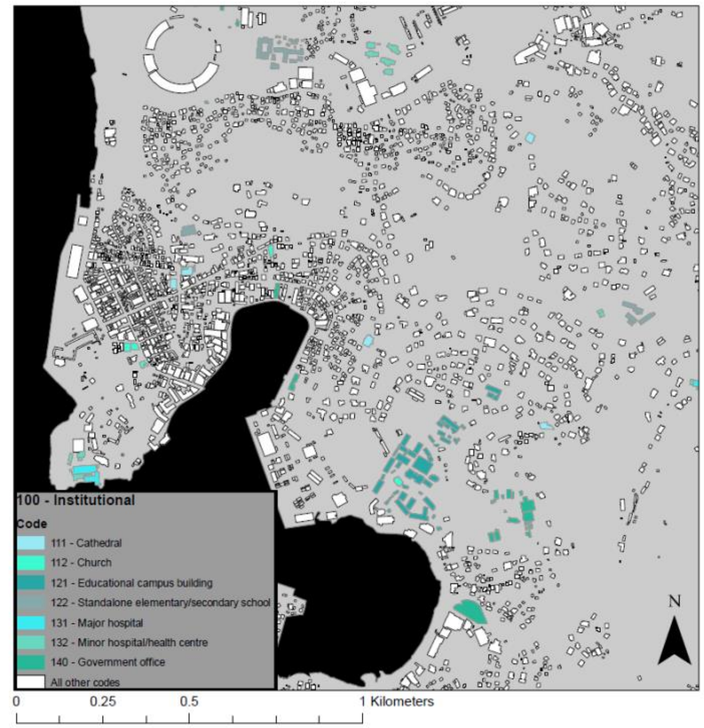


Figure 5: Left: Classification system for 100 – Institutional code buildings. Right: Implementation of the classification system on the test area in the Town of St George's.

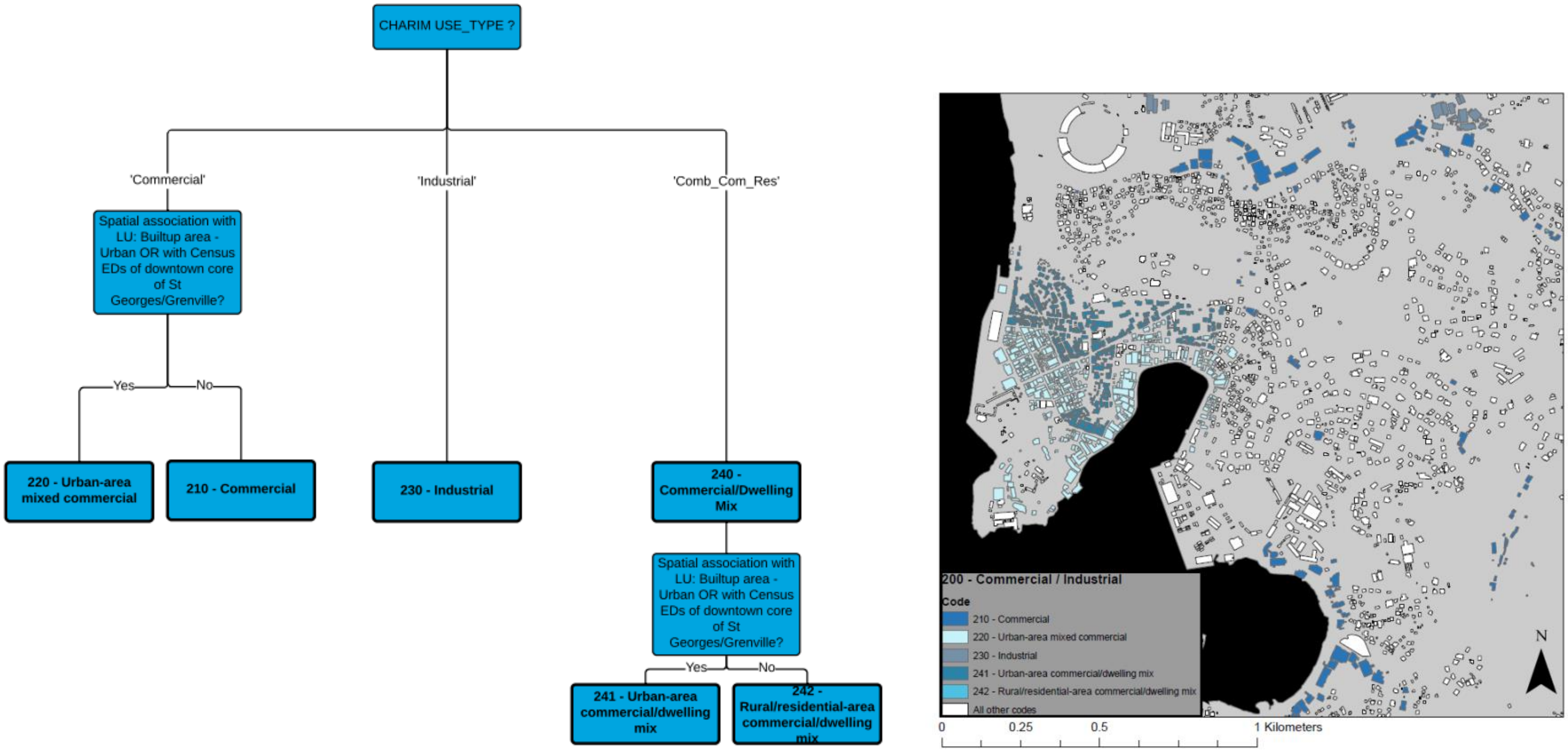


Figure 6: Left: Classification system for 200 – Commercial/Industrial code buildings. Right: Implementation of the classification system on the test area in the Town of St George's.

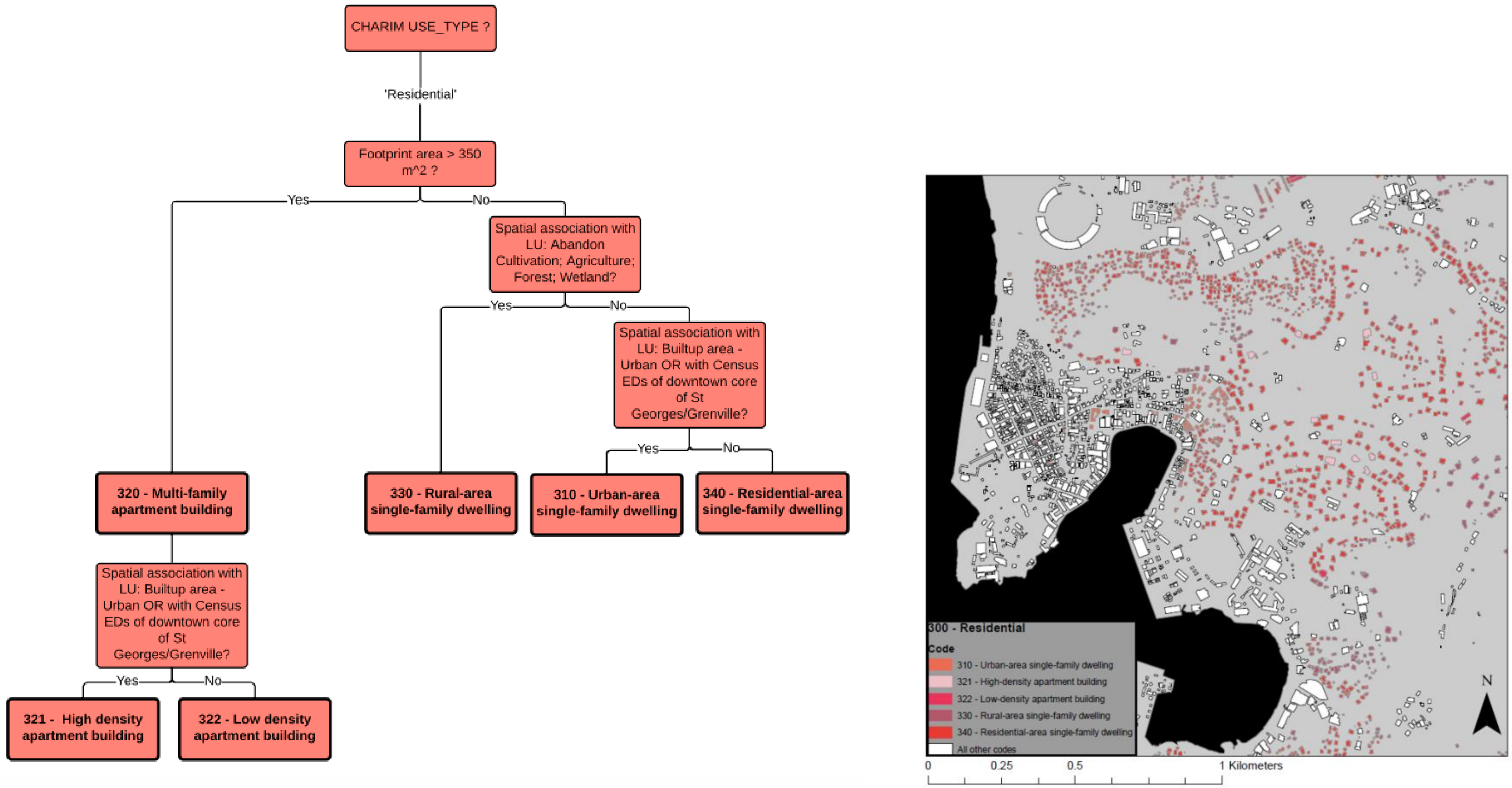


Figure 7: Left: Classification system for 300 – Residential code buildings. Right: Implementation of the classification system on the test area in the Town of St George's.

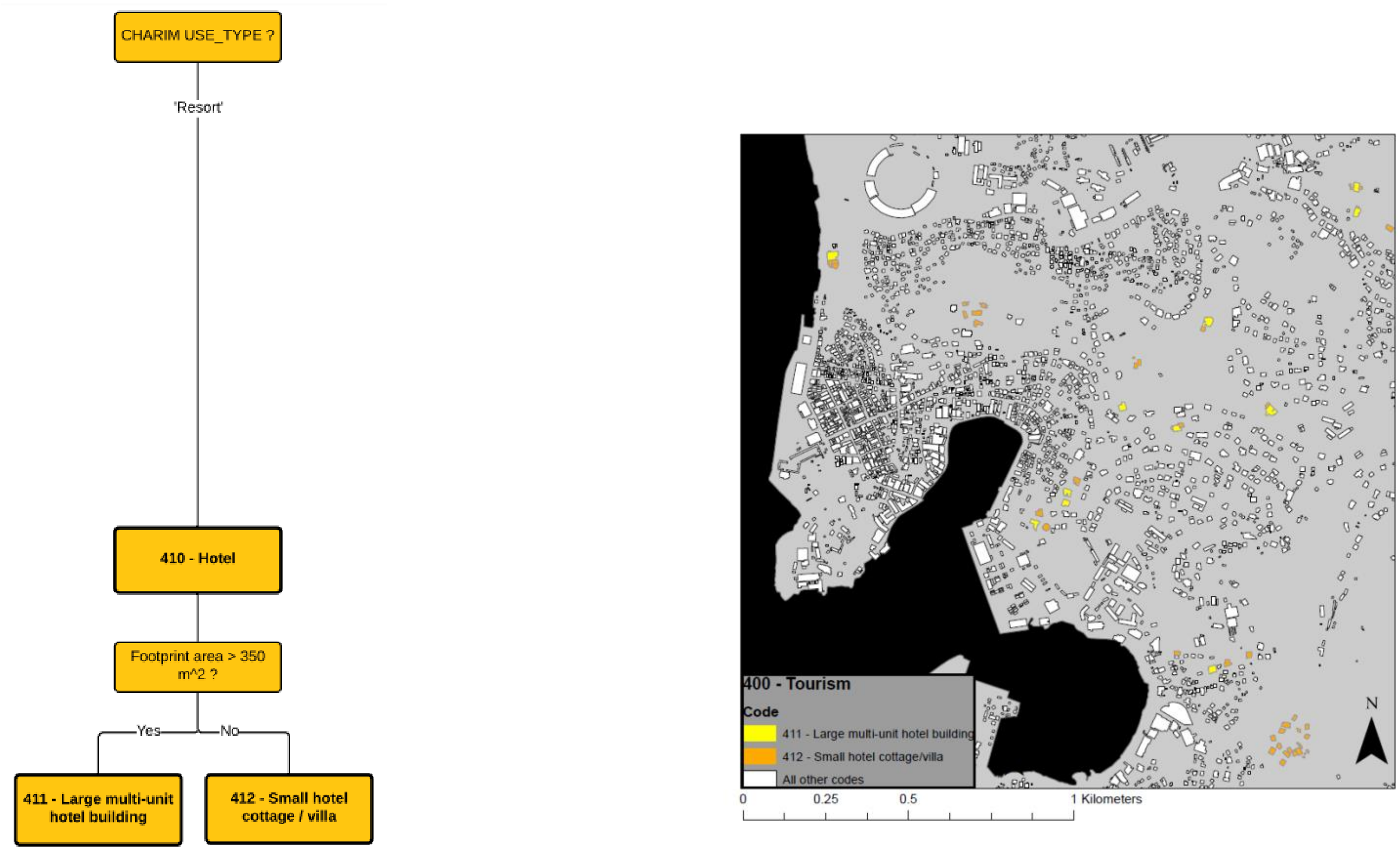


Figure 8: Left: Classification system for 400 – Tourism code buildings. Right: Implementation of the classification system on the test area in the Town of St George's.

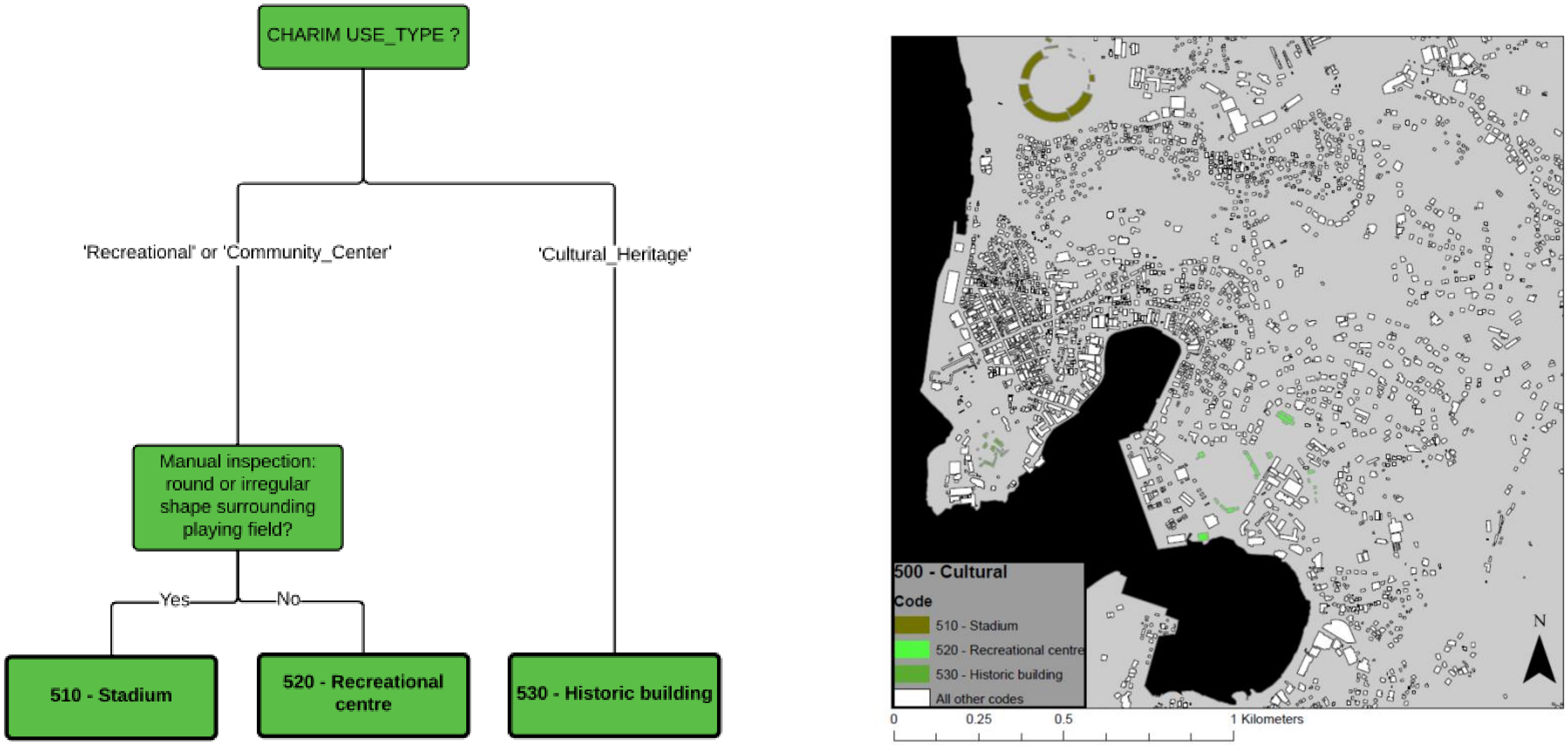
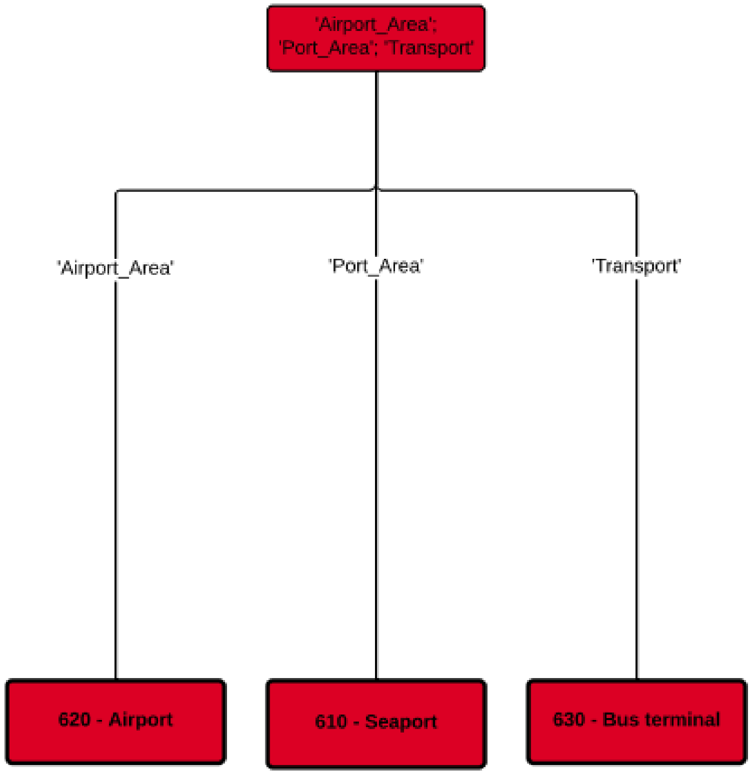


Figure 9: Left: Classification system for 500 – Cultural code buildings. Right: Implementation of the classification system on the test area in the Town of St George's.



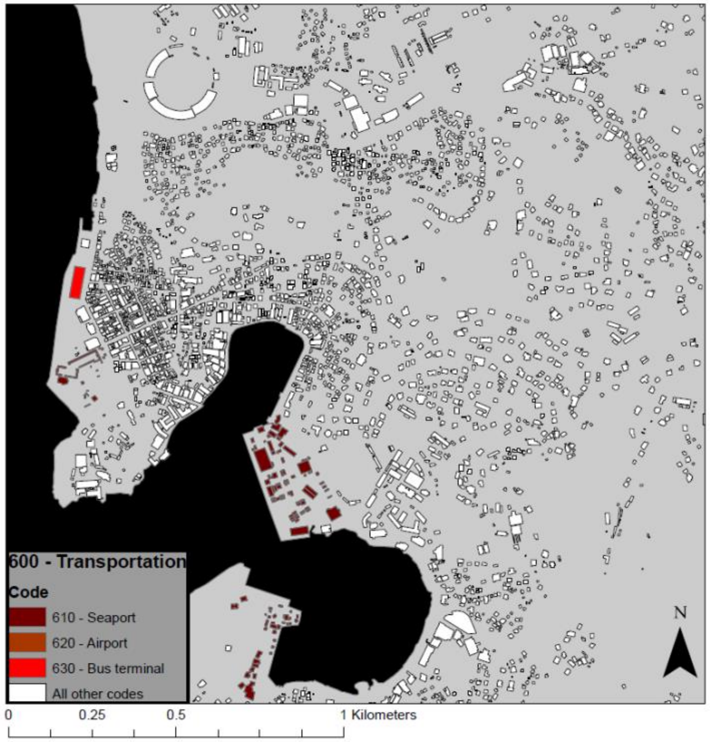


Figure 10: Left: Classification system for 600 – Transportation code buildings. Right: Implementation of the classification system on the test area in the Town of St George's.

3.2.2.2 Building height assumptions

After each footprint was classified, the occupancy classes were assigned an average building height that was based on observations from the composite image interpretation approach. Essentially, by looking at examples of each occupancy class using fieldwork photos, secondary image sources (Google, OpenStreetMap) and expert consultation (Telesford 2018) a reasonable building height assumption could be made. Since these assumptions were mostly based on the researcher's observations rather than a larger statistical source, it was important to conduct a sensitivity analysis on some of the larger occupancy classes to demonstrate how this part of the methodology affected final material stock calculations. This is detailed in Appendix C. Average height for each occupancy class is shown in Table 4, and a spatial distribution of the building heights in the Town of St. George's test area is shown in Figure 11.

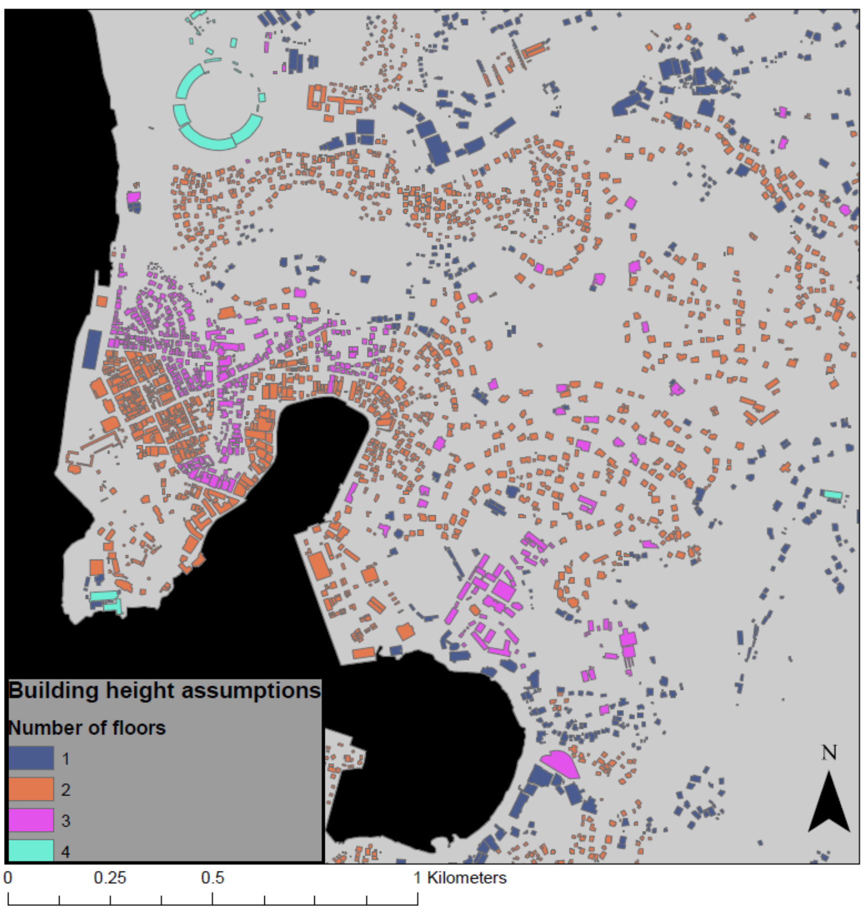


Figure 11: Building height assumptions mapped on the test area in the Town of St. George's.

3.2.2.3 Material intensity

The homogeneity of each occupancy class is considered a key assumption shared by stock-driven material stock analyses (Augiseau and Barles 2017), and requires that a set of material intensity typologies are defined that are accurately representative of the construction styles in the study area. Seven material intensity typologies were defined based on field work observations and photos, and codes of practice for construction given by CDERA (2005). These material intensity typologies are given in Table 5. As discussed earlier, the occupancy classification system was developed such that:

i. The buildings in any non-residential occupancy class[2] shared a single material intensity typology

ii. The buildings in any residential occupancy class[3] were distributed across multiple material intensity typologies based on percentages in the 2011 Housing and Population Census report (Central Statistics Office, 2011). Residential uses accounted for 80% of footprint area in the 2014 CHARIM data, so it was advantageous to make use of the census data to further refine the material stock calculations for these occupancy classes. The data table from the 2011 Housing and Population Census report was titled "Percentage Distribution of Households by Material of Construction and Parish". Categories for material of construction were Concrete (51.5%), Wood (33.7%), Wood and Concrete (13.9%), and Other (0.9%). Therefore, the material intensity typologies were allocated as shown in Table 3.

A comprehensive list of the material intensity typologies assigned to each occupancy class is shown in Table 4.

Table 3: Material intensity typology allocations for residential occupancy classes.

Census material category	**Percentage of households in Census (rounded to nearest 5%)**	**Material intensity typologies allocated under this category**	**Percentage allocations of material intensity typologies for each residential occupancy class**
Concrete	50%	Concrete Structure 1 (50%) Concrete Structure 2 (50%)	Concrete Structure 1: 25% Concrete Structure 2: 25% Timber Structure: 35% Concrete/Timber Mix Structure: 15%
Wood	35%	Timber Structure (100%)	
Wood and Concrete	15%	Concrete/Timber Mix Structure (100%)	
Other	0%	None	

[2] With the exception of code 230 - Industrial. This was assumed to be 80% Concrete Structure 2, 20% Steel Structure.

[3] With the exception of codes 321 – High density-area apartment and 322 – Low density-area apartment. These were assumed to always be a Concrete Structure 2.

Table 4: Average height assumptions and material intensity profiles for occupancy classes.

Code	Description	Average Height (# floors)	Material stock typology
111	Cathedral	3	Brick Historical Structure
112	Church/chapel	2	Concrete Structure 2
121	Educational campus building	3	Concrete Structure 2
122	Standalone elementary/secondary school	2	Concrete Structure 2
131	Major hospital	4	Reinforced Concrete Structure
132	Minor hospital/health center	1	Concrete Structure 2
140	Government office	2	Concrete Structure 2
210	Commercial	1	Concrete Structure 2
220	Urban-area mixed commercial	2	Concrete Structure 2
230	Industrial	1	80% Concrete Structure 2, 20% Steel Structure
241	Urban-area commercial/dwelling mix	3	Concrete Structure 2
242	Rural/residential-area commercial/dwelling mix	2	Concrete Structure 2
310	Urban-area single-family dwelling	2	25% Concrete Structure 1, 25% Concrete Structure 2, 35% Timber Structure, 15% Concrete/Timber Mix Structure
321	High density-area apartment	3	Concrete Structure 2
322	Low density-area apartment	2	Concrete Structure 2
330	Rural-area single-family dwelling	1	25% Concrete Structure 1, 25% Concrete Structure 2, 35% Timber Structure, 15% Concrete/Timber Mix Structure
340	Residential-area single-family dwelling	2	25% Concrete Structure 1, 25% Concrete Structure 2, 35% Timber Structure, 15% Concrete/Timber Mix Structure

411	Large multi-unit hotel building	3	Reinforced Concrete Structure
412	Small hotel cottage/villa	1	Concrete Structure 2
510	Stadium	4	Reinforced Concrete Structure
520	Recreational/community center	1	Concrete Structure 2
530	Historic building	2	Brick Historical Structure
610	Seaport	2	Concrete Structure 2
620	Airport	2	Reinforced Concrete Structure
630	Bus terminal	1	Concrete Structure 2

Table 5: Material intensity typologies used as a representative set of building construction styles in Grenada. Units: kg/m^2.

	Aggregate	***Timber***	***Concrete***	***Steel***
Concrete Structure 1				
Foundation - Pad footings	45	-	45	1
Foundation - Posts	-	-	300	5
Floors	-	-	450	10
Walls	-	-	520	1
Roof - Frame	-	40	-	-
Roof - Covering	-	-	-	10
Total	**45**	**40**	**1315**	**27**
Concrete Structure 2				
Foundation - Strip footings	135	-	225	5
Foundation - Ground slab	24	-	450	10
Floors	-	-	450	10
Walls	-	-	520	1
Roof - Frame	-	40	-	-
Roof - Covering	-	-	-	10
Total	**159**	**40**	**1645**	**36**
Timber Structure				
Foundation - Pad footings	45	-	45	1
Foundation - Posts	-	-	300	5
Floors	-	-	-	20
Walls	-	50	-	-
Roof - Frame	-	40	-	-
Roof - Covering	-	-	-	10
Total	**45**	**90**	**345**	**36**
Concrete/Timber Mix Structure				
Foundation - Strip footings	135	-	225	5
Foundation - Ground slab	24	-	450	10
Floors	-	-	450	10
Walls	-	50	-	-
Roof - Frame	-	40	-	-
Roof - Covering	-	-	-	10
Total	**159**	**90**	**1125**	**35**
Steel Structure				
Foundation - Strip footings	135	-	225	5
Foundation - Ground slab	24	-	450	10
Floors	-	-	450	10
Walls	-	-	520	145
Roof - Frame	-	-	-	145
Roof - Covering	-	-	-	10

Total	**159**	**0**	**1645**	**325**
Brick Historical Structure				
Foundation - Strip footings	135	-	225	5
Foundation - Ground slab	24	-	450	10
Floors	-	-	-	20
Walls	-	50	-	-
Roof - Frame	-	40	-	-
Roof - Covering	-	-	-	-
Total	**159**	**90**	**675**	**35**
Reinforced Concrete Structure				
Foundation - Strip footings	135	-	225	5
Foundation - Ground slab	24	-	450	10
Floors	-	-	450	10
Walls	-	-	-	145
Roof	-	-	-	10
Total	**159**	**0**	**1125**	**180**

3.2.3 Calculating material stock

With building height and material intensities established for the building footprints, the material stock could then be calculated. For a material i (aggregate, concrete, timber, or steel), the total stock MS_i in buildings was calculated using the equation

$$MS_i = \sum_{OC} MI_{i,OC} \times GFA_{OC} \qquad (1)$$

where $MI_{i,OC}$ is the intensity of material i in occupancy class OC. For an occupancy class where more than one material intensity typology has been allocated, $MI_{i,OC}$ is calculated as a weighted average across the given typologies. GFA_{OC} is the gross floor area for all buildings in occupancy class OC, calculated by equation (2):

$$GFA_{OC} = Average\ height_{OC} \times Total\ footprint\ area_{OC} \qquad (2)$$

3.2.4 Mapping spatial distributions

Occupancy class, material intensity, and material stock were added as attributed to the 2014 building footprints shapefile in ArcGIS as the methodology was carried out, so that the spatial distribution of the material stock could be mapped easily. Two national-scale maps of material stock distribution were produced: One using a raster that summed the material stock in 0.01 sq.

km cells; and a second map that showed the material stock per unit area for each census enumeration district.

For visualization purposes, a building with occupancy class that had more than one material intensity typology allocation (e.g. residential buildings) was given the weighted average of the material intensities. This provided a sort of "average" distribution for local scale maps (e.g. a zoomed in map of the Town of St George's); but it should be noted that true single-building resolution is not obtained from this methodology.

3.3 Methodology for analyzing future stock loss scenarios

3.3.1 Extreme weather

The objective of this methodology was to integrate historical hurricane impact data with the 2014 building material stock account to develop a 2014 stock loss scenario; that is, to estimate stock lost where an identical event to Hurricane Ivan hits 2014 material stocks – an "Ivan-II" scenario. The World Bank assessed the damages due to Hurricane Ivan on September 17, 2004, ten days after the tropical cyclone struck Grenada. The specific dataset used in this scenario is an assessment of damages in the housing sector by Parish (the geographical divisions in Grenada), as shown in Table 6. The damage scale used by the World Bank in this assessment primarily refers to the level of damage to the roof structure and covering. This is likely due to the characteristics of Ivan; it was considered a "dry" storm and damages were mainly from high winds rather than flooding or landslides. As a result, the Ivan-II stock loss scenario developed here focused on timber in the roof and walls. For each of the six damage levels given, a percent stock loss was assigned. This was done for three different "Loss scenarios" of varying severity, as seen in Table 7. Each scenario was implemented Parish-by-Parish in ArcGIS, and total material lost was calculated as well as material stock lost by Parish and by census enumeration district (absolute and per unit area values). ArcMap was used to map these losses across the entire island.

Table 6: Percent of homes damaged, by Parish, during Hurricane Ivan. Source: Grenada, Hurricane Ivan - Preliminary Assessment of Damages, September 17, 2004 -The World Bank.

Parish	ND	Level 1	Level 2	Level 3	Level 4	Level 5
St. Patrick	30%	30%	20%	15%	5%	0%
St. Mark	30%	30%	25%	10%	5%	0%
St. John	20%	25%	35%	15%	5%	0%
St. Andrew	5%	15%	20%	30%	20%	10%
St. David	0%	5%	10%	20%	50%	15%
St. George	0%	5%	10%	20%	50%	15%

Legend:
ND – No damages
Level 1 – Windows, doors and furnishing destroyed or damaged
Level 2 – Partial roof covering destroyed or damaged
Level 3 – Roof structure destroyed or damaged
Level 4 – Complete roof destroyed
Level 5 – Significant damage to structural frame

Table 7: Percentage of timber stock loss corresponding to World Bank damage levels for three "Loss scenarios".

Loss scenario	ND	Level 1	Level 2	Level 3	Level 4	Level 5
Low	0%	0%	0%	10%	50%	75%
Mid	0%	0%	0%	20%	60%	85%
High	0%	0%	0%	35%	75%	100%

3.3.2 Sea-level rise

The second type of scenario considered was material stock lost due to sea-level rise. The goal of this methodology was to illuminate how much of Grenada's material stock is exposed to sea-level rise, and of this stock, which services or sectors are most vulnerable. Three sea-level rise scenarios were considered: 1 meter (SLR1), 2 meters (SLR2), and 3 meters (SLR3). This range was chosen based on the likelihood of a 1 to 2 meter increase above present sea levels by the year 2100 (Simpson et al., 2010), and SLR3 presents a more severe situation as sea levels continue to rise during the 22nd century. These estimates were made using the Digital Elevation Model raster available from the CHARIM project, which was imported to ArcGIS. 1, 2 and 3 meter elevations were converted to polygon shapefiles and overlaid with the 2014 building footprints to allow for calculation of stock "exposed" to rising sea levels.

3.4 Methodology for material flow analysis (MFA)

This section describes the economy-wide MFA for construction materials in Grenada. The goal of this section of the methodology is to provide a time-series account of the domestic extraction and trade used to supply inputs to the material stock, referred to as the gross addition to stock (GAS). Economy-wide data from secondary sources are compiled, and thus the calculated GAS is an economy-wide measure, including construction of both buildings and other infrastructure.

3.4.1 Indicators for construction material flows

This section defines the headline MFA indicators calculated in this study. Definitions of indicators 1) through 5) are from (Eurostat 2013), while 6) is a derived indicator from the methodology of Krausmann et al. (2017).

1) *Domestic extraction (DE):* Domestic extraction is the annual quantity of raw materials extracted from the natural environment in Grenada's national territory to be used as primary inputs for economic production. The key component of construction material domestic extraction for Grenada are nonmetallic minerals.
2) *Imports:* Imports are the annual quantities of raw, semi-processed and processed materials traded from the rest of world (ROW) into Grenada's physical borders.
3) *Exports:* Exports are the annual quantities of raw, semi-processed and processed materials traded out of Grenada's physical borders to the ROW.
4) *Physical trade balance (PTB):* Physical trade balance is an indicator of the net physical inflow of goods to Grenada's economy. In this study, a positive PTB indicates Grenada is a net importer of construction materials whilst a negative PTB indicates it is a net exporter of construction materials. PTB for a material i is calculated as follows:

$$PTB_i = Imports_i - Exports_i \tag{3}$$

5) *Domestic material consumption (DMC):* Domestic material consumption is an indicator measuring all construction materials used by the economy in Grenada in one year. It accounts for the construction materials extracted within its national territory (i.e., DE) and the net flow of physical trade with the ROW (i.e., PTB). DMC for a material i is calculated as follows:

$$DMC_i = DE_i + Imports_i - Exports_i \tag{4}$$

6) *Gross addition to stock (GAS):* This indicator estimates the annual portion of the DMC of construction materials that are input to the material stock, after losses due to processing and manufacturing. The processing and manufacturing loss rates used correspond those used by the MISO model of global material stocks (Krausmann et al., 2017). For a given material i, inputs to stocks from DMC are given by the equation

$$GAS_i = DMC_i \times (1 - Processing\ loss\ rate_i)(1 - Manufacturing\ loss\ rate_i) \quad (5)$$

Where applicable, per capita values of the indicators were calculated using population data from The World Bank (2017).

3.4.2 Data compilation and sources

The collated data for this MFA Grenada covers domestic extraction (DE), imports and exports of construction materials in time series from 1993 to 2009. The Eurostat (2013) methodological guidelines for MFA provide categorization structure covering 47 material types, which are aggregated under 4 main categories: biomass, metal ores, non-metallic minerals, and fossil energy materials. Since this study focused only on construction materials, Table 8 provides an overview of the materials covered in this MFA.

Table 8: Overview of Eurostat (2013) material types considered for an MFA of construction materials.

Eurostat material classification	**Sub-classification**	**Sub-grouping**
Biomass	Wood	Timber (industrial round-wood)
		Wood products
Metal ores	Iron	
	Non-ferrous metal ores and concentrates	Copper
		Nickel
		Lead
		Zinc
		Tin
		Bauxite and other aluminum
	Products mainly from metals	Iron
		Copper
		Nickel

		Lead
		Zinc
		Tin
		Bauxite and other aluminum
Non-metallic minerals	Marble, granite, sandstone, porphyry, basalt, other ornamental or building stone (excluding slate)	
	Chalk and dolomite	
	Slate	
	Limestone and gypsum	
	Clays and kaolin	
	Sand and gravel	
	Other n.e.c.	Bitumen and asphalt (for road const.)
		Feldspar (for ceramic)
	Products mainly from non-metallic minerals	Articles of cement, concrete or artificial stone

3.4.2.1 Domestic extraction

Annual quantities of domestic extraction (DE) were not available from and national or international sources, so DE was approximated based on expert interviews during field work and Eurostat (2013) methodological guidelines. An overview is provided in Table 9.

Table 9: Overview of domestic extraction activity for construction purposes in Grenada, 1993 to 2009.

Material category	**Domestic extraction**
Timber	None[1, 2, 3]
Iron	None[4]
Non-metallic minerals	DE of volcanic rock and sand for construction purposes[2, 4]
Other metals	None[2, 4]

[1]Grenada Ministry of Agriculture & Lands, Forestry Division (2017). Local lumber industry is for building furniture and smaller products.
[2]Grenada Ministry of Infrastructure Development, Physical Planning Unit (2017).
[3]TA Marryshow Community College, Mirabeau Campus (2017).
[4]United States Geological Survey Mineral Yearbooks (1994-2009).

3.4.2.1.1 DE of sand and gravel

Sand and gravel production data were not available from national statistical sources, so DE was estimated based on guidelines from the UNEP-IRP Global Material Flows Database (UNEP-IRP, 2018). When statistics are inadequate, the database estimates total quantity of sand and gravel extraction using the coefficients derived in Miatto et al. (2017). The steps taken to estimate sand and gravel DE for Grenada are as follows[4]:

1. Calculate sand and gravel inputs to concrete production based on the DMC of cement using equation (6):

$$Sand\ \&\ gravel\ input_{concrete}\ [t] = DMC_{cement}[t] \times\ \lambda_{concrete} \tag{6}$$

   where $\lambda_{concrete} = 5.26$ (Miatto et al., 2017). This is the most recently derived value in the literature; however, several larger values for $\lambda_{concrete}$ have been used in past studies and are summarized in Table 10. A sensitivity analysis of the DE results based on the value of $\lambda_{concrete}$ used is shown in Appendix C.

[4] Miatto et al. (2017) also includes three additional construction uses of sand and gravel which are considered by UNEP-IRP (2018) in the Global Material Flows Database: production of bricks; production of cement; and construction of railways. There was no indication of domestic production of cement or brick, and Grenada has no railways, so these calculations were not necessary for this study.

Table 10: Values in literature for calculating input [t] of sand and gravel per unit consumption [t] of cement.

Source	$\lambda_{concrete}$	**% difference from Miatto et al. (2017)**
Miatto et al. (2017)	**5.26**	--
Eurostat (2013)	6.09	+15.8%
Krausmann et al. (2009)	6.5	+23.6%
Weisz et al. (2007)	6.1	+16.0%

2. Calculate sand and gravel inputs to asphalt concrete and sublayers for construction of transport infrastructure, based on the DMC of bituminous material (asphalt) using equation (7):

$$Sand\ \&\ gravel\ input_{asphalt}\ [t] = DMC_{asphalt}[t] \times\ \lambda_{asphalt} \tag{7}$$

where $\lambda_{asphalt} = 51.12$ (Miatto et al., 2017).

3. Calculate the sand and gravel used as sublayers for buildings, based on the DMC of cement using equation (8):

$$Sand\ \&\ gravel\ input_{sublayers}\ [t] = DMC_{cement}[t] \times\ \lambda_{sublayers} \tag{8}$$

where $\lambda_{sublayers} = 0.42$ (Miatto et al., 2017).

4. The values calculated using equations 7 and 8 are inputs to material stock. Krausmann et al. (2017, supporting info) note that sand and gravel are separated before mixing with cement, and estimate 4% manufacturing losses. Thus the total estimate for sand and gravel DE is calculated as

$$DE_{sand\&gravel} = \left(Sand\ \&\ gravel\ input_{concrete} + Sand\ \&\ gravel\ input_{asphalt}\right)/0.96 + Sand\ \&\ gravel\ input_{sublayers} \tag{9}$$

3.4.2.2 Import and export trade flows

Import and export data was collated from secondary international trade statistics in the United Nations Comtrade database (UN Comtrade, 2017). An exhaustive list of the commodities from the database can be found in Appendix D. For almost all construction materials studied, UN Comtrade reports trade flows in both net weight (kilograms) and trade value (US$). For certain commodities that were reported only as trade value, the following procedures were used to calculate the mass of the trade flow:

I. *Wood products*: Net weight and trade value were both reported in a previous/subsequent year, so the net weight per unit trade value was calculated and used for the year(s) in question.

II. *Metals*: Net weight was calculated using annual metal prices from the United States Geological Survey. Since this study is concerned with the mass of metals imported/exported (and not quantities of ore extraction outside the system boundary), this was confirmed to be an acceptable conversion method after consultation with an MFA expert (West 2018, personal correspondence).

III. *Non-metallic minerals*: No conversions were necessary for items in this category.

3.4.2.3 Gross addition to stock from DMC

Calculating gross addition to stock (GAS) accounts for material throughput as losses due to processing and manufacturing. As shown in equation (3), there are two coefficients needed to calculate the GAS for each material: the processing loss rate and manufacturing loss rate. The loss rates used in this study are the same as those used by Krausmann et al. (2017) for the Material Inputs, Stocks and Outputs (MISO) model, and are given below in Table 11. This table corresponds to the material types reported in the MISO database, and the stage of processing/manufacturing they have undergone. When working with the commodities reported from the UN Comtrade database in this study, it was important to identify how ‘processed’ a specific commodity was upon import to Grenada; i.e., would stocking of material include losses due to processing, manufacturing or both. It is important to note that although Krausmann et al. (2017) report a range of values for processing losses associated with metals, Grenada imported virtually no metal ores or concentrates that these rates apply to, so this uncertainty is not introduced into the results.

Table 11: Summary of processing and manufacturing loss rates for stock-building materials. From Krausmann et al. (2017, sup. info).

Stock-building materials (MFA)	Primary material inputs to stock	Processing losses	Manufacturing losses
Industrial roundwood	Solid wood	10%	27%
Iron ore	Iron and steel	42–58%	17.5%
Copper ore	Copper	96–99%	2.7%
Bauxite	Aluminum	80–86%	7.6%
Other ores and minerals	Other metals and minerals	91–97%	9.2%
Crude oil/natural gas	Plastics	n.d.	10%
Crude oil	Bitumen/asphalt	n.d.	4%
Limestone, gypsum, clay	Cement/concrete	44%	4%
Clay	Bricks	26%	4%
Sand and gravel	Split into sand and gravel used in concrete and asphalt	0%	4%
	Sand and gravel required as sub-base and base-course layer for road and building construction	0%	0%

4 Results

4.1 Material Stock (MS) in buildings

This subsection presents the results of the Methodology described in Section 3.2. The quantity and quality of the material stock is shown by considering the overall share of material types and building use-types. Per capita results are also given where applicable. Following this, the spatial distribution of the material stock in buildings is shown in several national- and sub-national-scale maps.

4.1.1 Material Stock (MS) by material category

Total material stock in buildings in 2014 was calculated to be 11,959 kilotonnes, equalling 112 tonnes per capita given that year's population. As seen in Figure 12 below, concrete accounted for the largest share of MS at nearly 84.72%, with much smaller shares for aggregate (8.06%), timber (3.77%) and steel (3.45%). This is reflective of the majority of building typologies in Grenada being highly concrete-intensive for structural components.

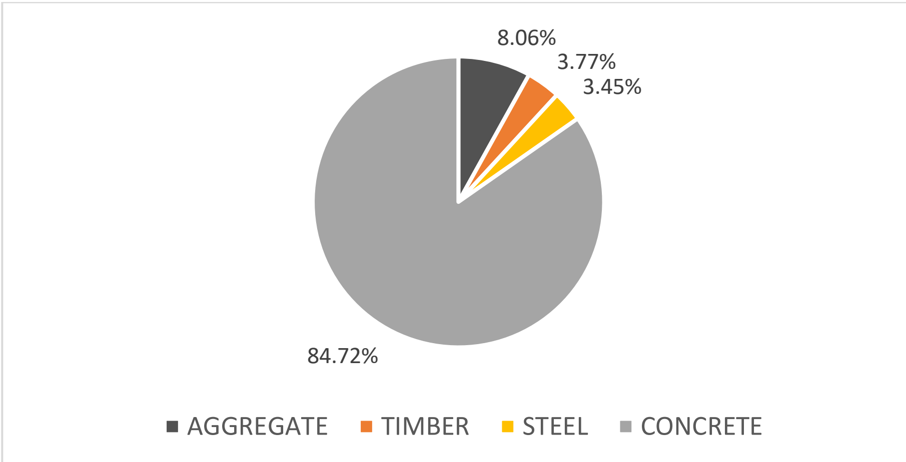


Figure 12: Total share (%) of material stock in buildings by material category. Total estimated MS was 11,959 kt.

4.1.2 Stock by building use-type

As seen in Figure 13, the total MS is largely dominated by residential buildings, accounting for 8,001 kt or 66.91% of MS. Absolute values can be found in Table 12. In terms of per capita levels, residential buildings account for 75 t/cap. As discussed in the previous section, concrete is the predominant structural material in most construction types, and makes up between 83% and 86% of the stock in any given category. Table 13 and the corresponding charts in Figure 14 show the percent share of materials by building use-type, and the proportions are similar to the aggregated results shown in Figure 13; this is reflective of the fact that construction typologies are generally shared across different occupancy classes in Grenada.

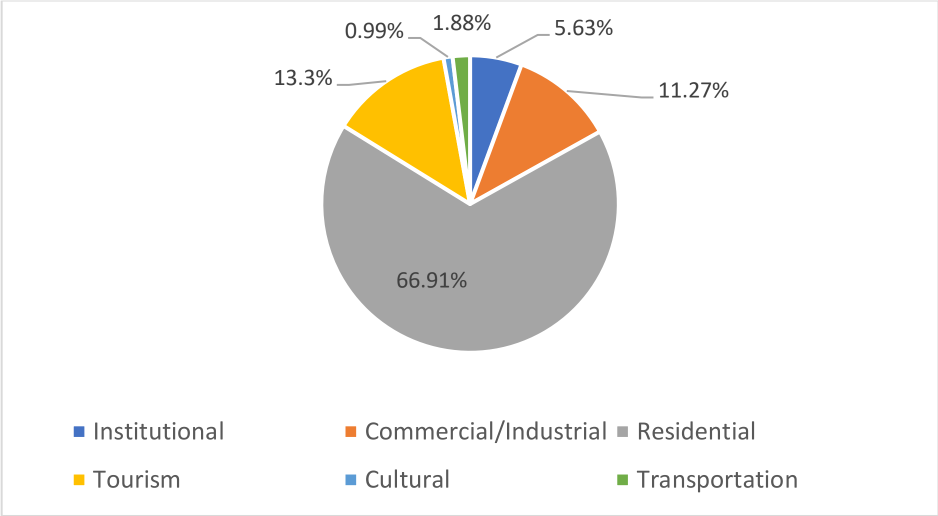


Figure 13: Total share (in %) of material stock in Grenada's buildings, 2014, by use-type. Total estimated MS was 11,959 kt.

Table 12: Breakdown of material stock per capita in building use-types by material category. Units: t/cap.

Use-type	**AGGREGATE (t/cap)**	**TIMBER (t/cap)**	**STEEL (t/cap)**	**CONCRETE (t/cap)**	**Total (t/cap)**
Institutional	0.6	0.2	0.2	5.4	6.3
Commercial/Industrial	1.2	0.3	0.4	10.8	12.7
Residential	5.7	3.7	2.0	63.8	75.2
Tourism	1.2	0.1	1.1	12.6	15.0
Cultural	0.1	0.0	0.1	0.9	1.1
Transportation	0.2	0.0	0.1	1.8	2.1

Table 13: Breakdown of material stock in building use-types by material category (percentage). Total estimated MS was 11,959 kt.

Use-type	**AGGREGATE (%)**	**TIMBER (%)**	**STEEL (%)**	**CONCRETE (%)**
Institutional	9.5%	2.5%	2.5%	85.4%
Commercial/Industrial	9.7%	2.3%	3.0%	84.9%
Residential	7.6%	4.9%	2.7%	84.8%
Tourism	8.1%	0.4%	7.7%	83.8%
Cultural	8.7%	0.8%	7.9%	82.7%
Transportation	9.6%	1.8%	4.4%	84.2%

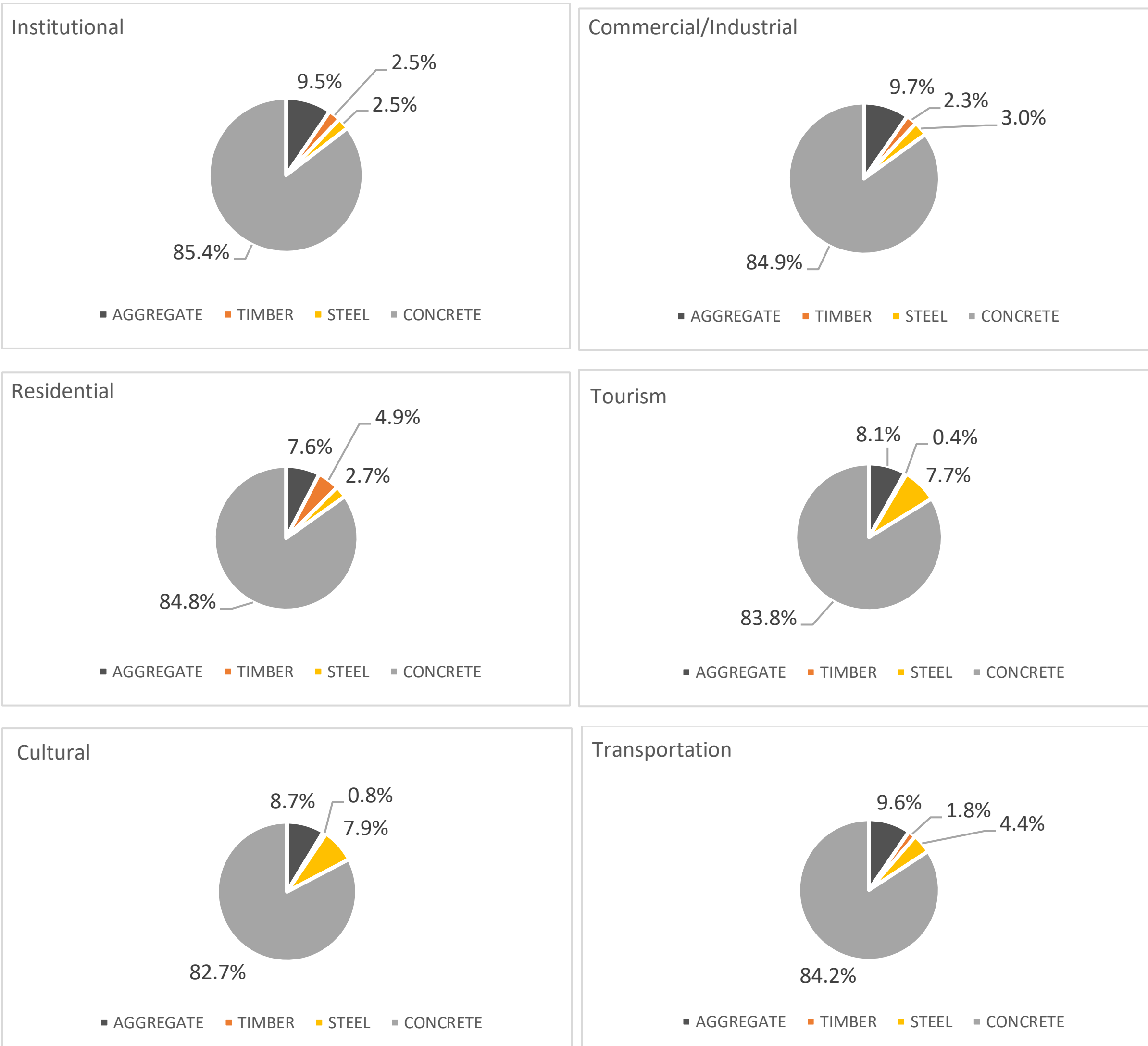


Figure 14: Breakdown of material stock in the six building use-types by material category (corresponding data in Table 13).

4.1.3 Spatial distribution

Addressing the first objective of this research, the spatial distribution of material stock for the entire island of Grenada is presented in two different formats in Figure 15 and Figure 16 to show what and where the concentration of material stocks are. Figure 15 shows the density of total material stock by breaking the island into a grid of 0.01 sq. km (10,000 m^2) cells, providing a resolution that traces out the denser urban and residential areas, as well as providing an idea of the development of buildings along roadways through the mountainous interior region. The densest pockets of material stock (dark orange or red) show the location of the main towns and cities in Grenada, all located near the coast. The southwestern part of the island (St. George's Parish) contains a disproportionate share of the stock, where a large part of the population resides and most commercial activity occurs, including the main ports of entry, beach resorts, post-secondary education and government. A second cluster can be seen on the east coast of the island; this is Grenville, Grenada's second-largest urban centre (to the Town of St. George's) and the location of a secondary, smaller port for trade.

Figure 16 presents the material stock distribution by Census Enumeration District (ED), and is meant to be supplementary to the aforementioned map. While some resolution is lost with this map, it does showcase the integration of the material stock data with traditional government statistics in the geodatabase, having potential used for public planners.

Following these are local-scale distributions for two built-up areas in Grenada: The Town of St. George's (Figure 17), and the commercial-industrial district at the southwestern tip of the island (Figure 18). Again, it should be emphasized that the methodology for calculating material stock does not provide single-building resolution, however these local-scale maps still provide an interesting picture of the "average" spatial distribution of materials across different locales in Grenada. While the national-scale maps indicate the extent of coastal concentrations of stocks, these local-scale maps show that within these built-up areas, many of the buildings are situated directly on the shoreline.

4.1.3.1 Country-wide distributions

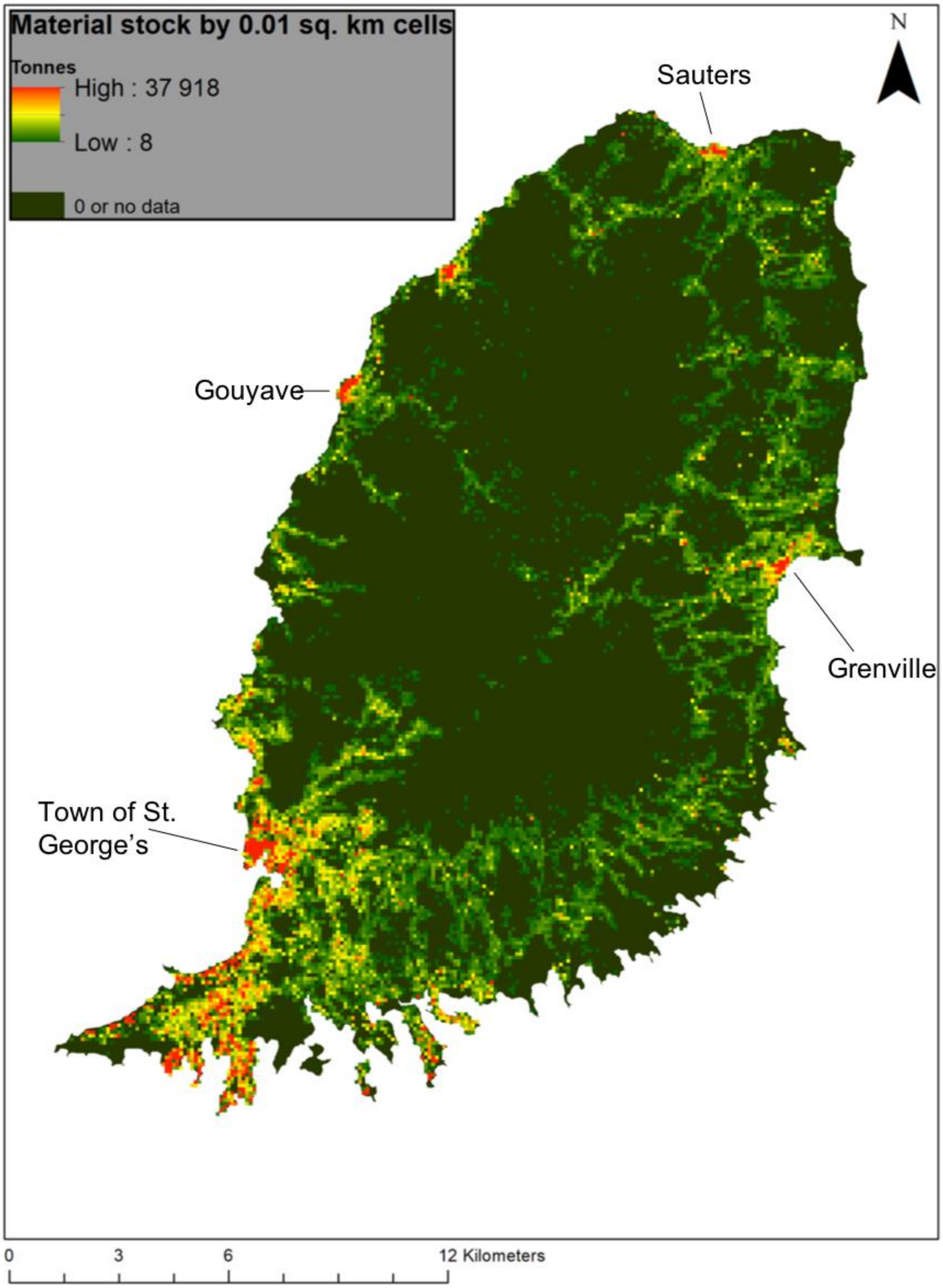


Figure 15: Density of material stock in buildings in Grenada in 2014. Cell size is 0.01km^2 (10,000 m^2).

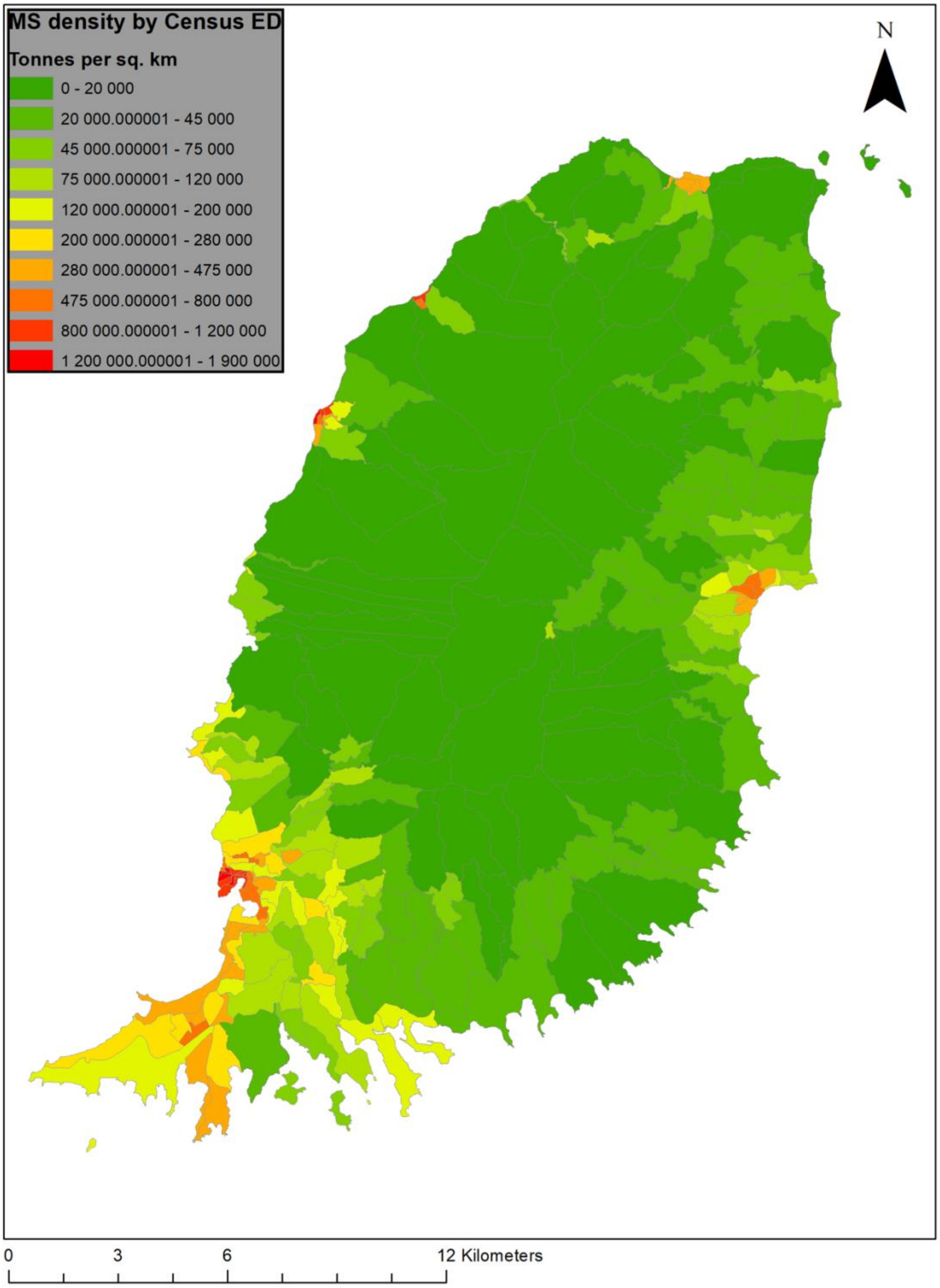


Figure 16: Material stock density in buildings in Grenada in 2014, by census enumeration district.

4.1.3.2 Local-scale distributions

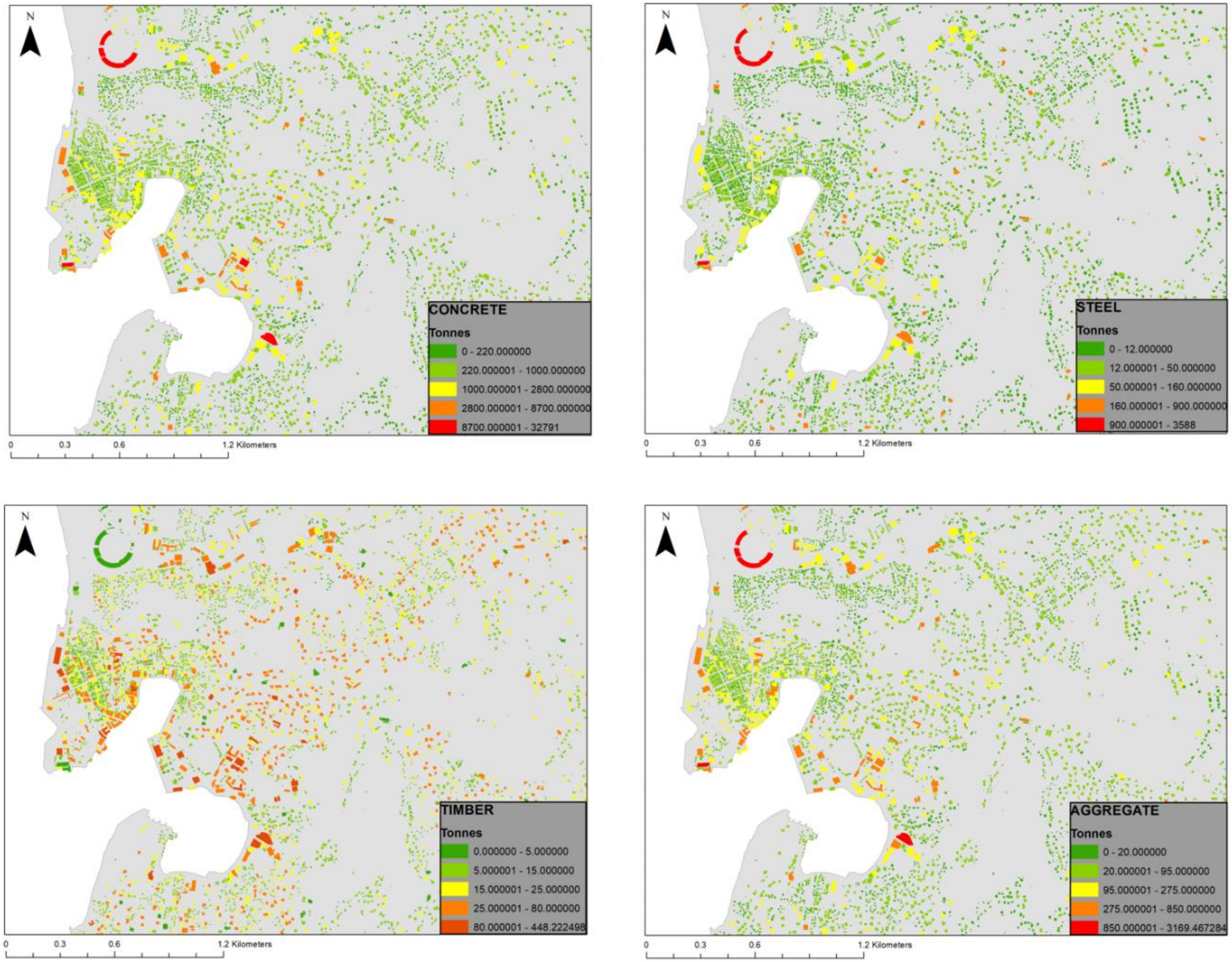


Figure 17: Local -scale distribution of material stock in buildings in the Town of St. George's (absolute values). Top left: concrete; Top right: steel; Bottom left: timber; Bottom right: aggregate.

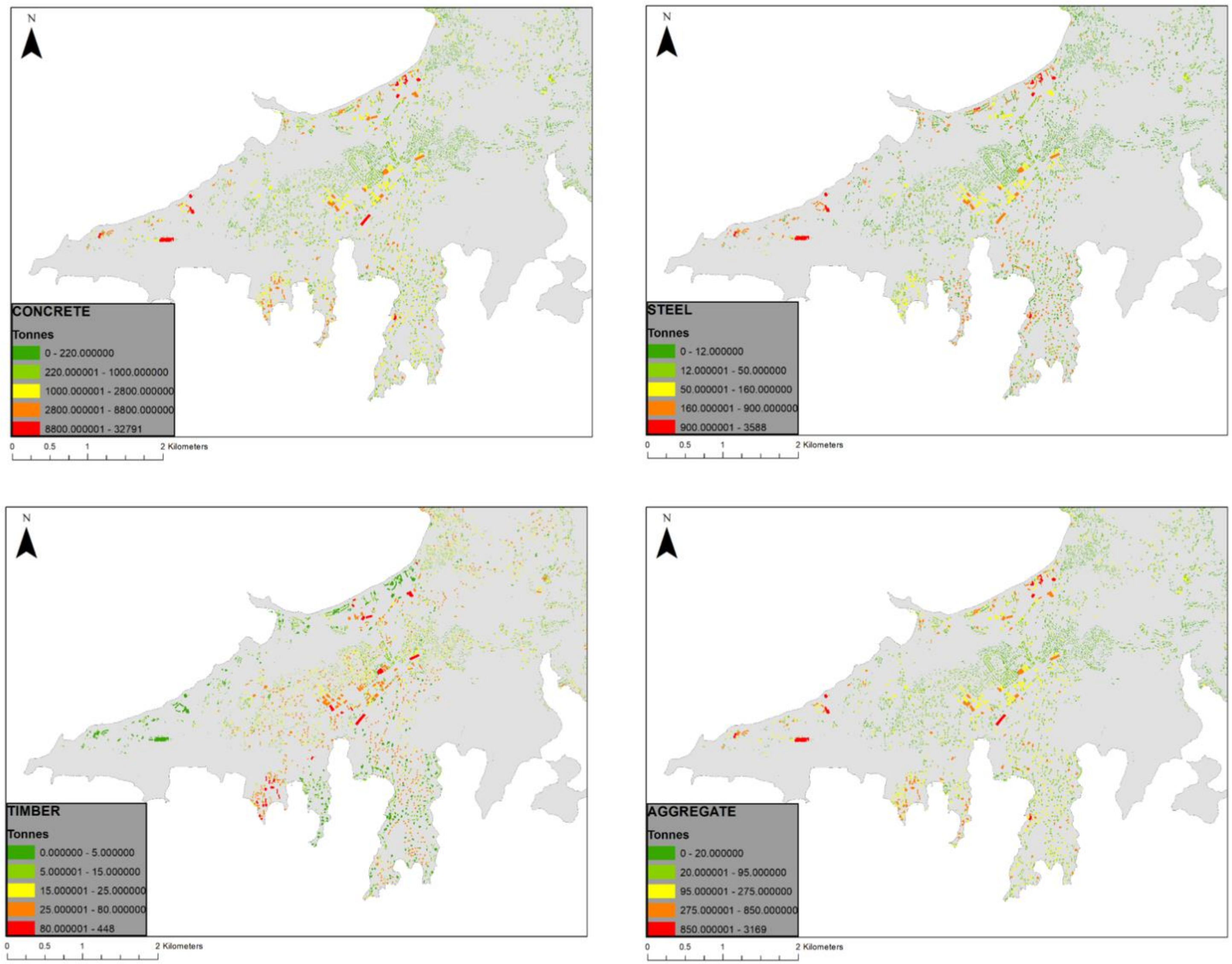


Figure 18: Local -scale distribution of material stock in buildings in the southwestern commercial district (absolute values). Top left: concrete; Top right: steel; Bottom left: timber; Bottom right: aggregate.

4.2 MFA of construction materials (1993 – 2009)

This subsection presents the results of the MFA methodology described in Section 3.4. The headline result of this section is the gross addition to stock (GAS), however the domestic extraction (DE), physical trade balance (PTB) and domestic material consumption (DMC) indicators are first presented to provide a full picture of how Grenada added to its material stock between 1993 and 2009.

4.2.1 Domestic extraction (DE)

As discussed in Section 3.4.2.1, the only raw materials domestically produced for construction in Grenada are non-metallic minerals (i.e. sand and gravel). DE for these materials is shown below in Figure 19 along with per capita levels for the time period 1993 to 2009. No clear trend is apparent over this time period, with average DE at 3.8 t/cap and ranging from 2.4 t/cap to 5.4 t/cap, and while Grenada started a DE of 404 kt in 1993 DE was 400 kt in 2009.

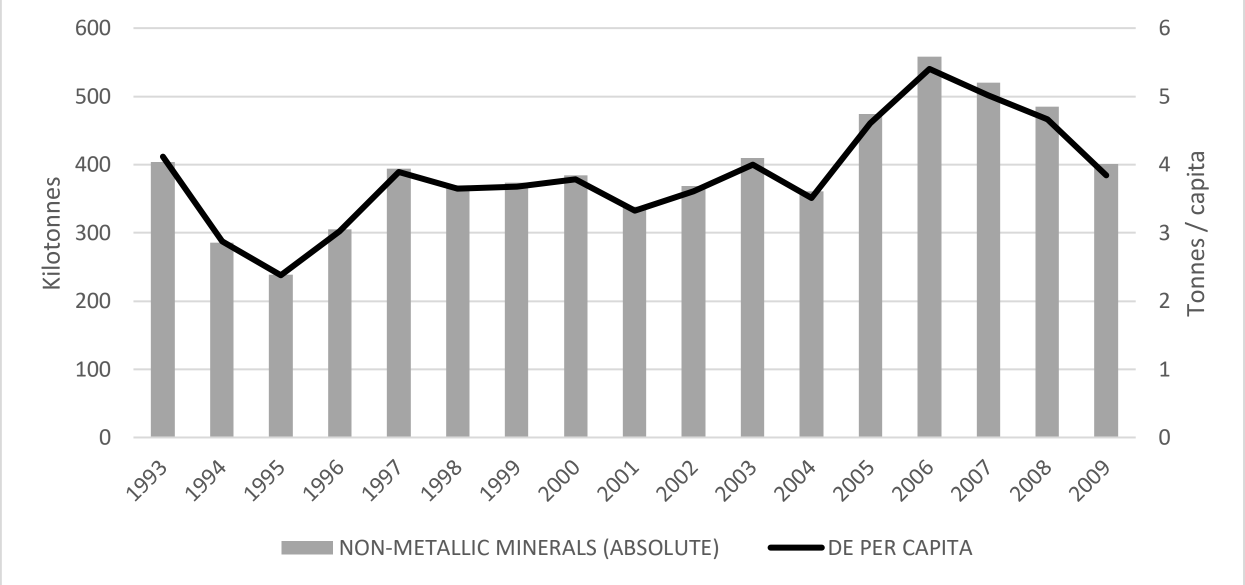


Figure 19: Domestic extraction (left axis) in Grenada from 1993 to 2009, with per capita values also plotted (right axis).

Total DE over this time period can also be broken down by the end-uses for the material (Figure 20). 77.7% of non-metallic minerals were used as mix in concrete production, whilst the remaining share was used for transport infrastructure (16.4%) and building sublayers (5.9%).

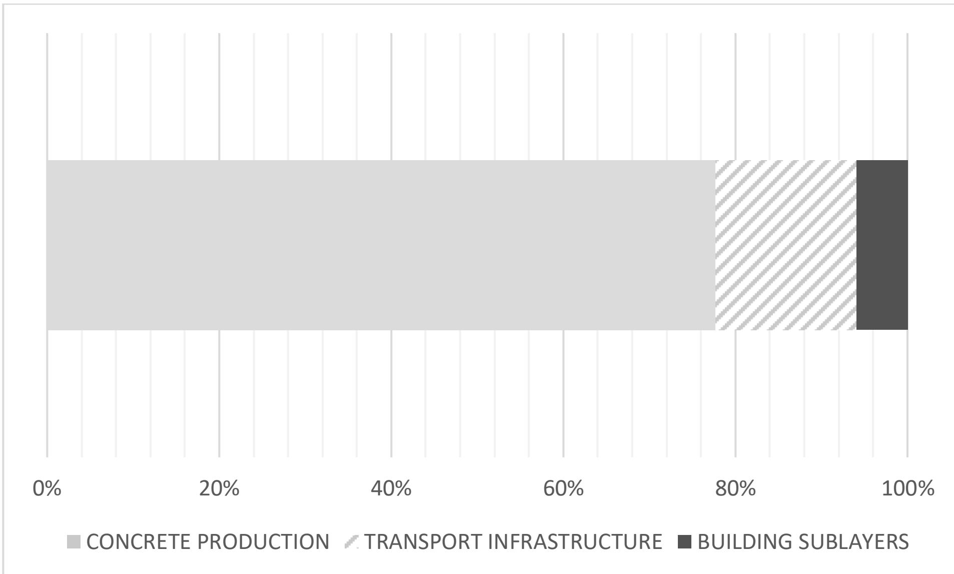


Figure 20: Breakdown of uses for domestic extraction of non-metallic minerals in Grenada over the period of 1993 to 2009. These shares are estimated based on the methodology from Miatto et al. (2017) (see Methodology section).

4.2.2 Imports and Exports

Grenada's imports are shown in Figure 21, and exports in Figure 22. Imports range from 0.5 to 1.5 tonnes/capita. Aside from iron and steel, the Grenadian economy exported almost no construction materials over this time period – less than 0.03 tonnes/capita. Because Grenada is so highly import-dependent for construction materials, the trends for the physical trade balance follow closely to the imports results presented here (see the following section).

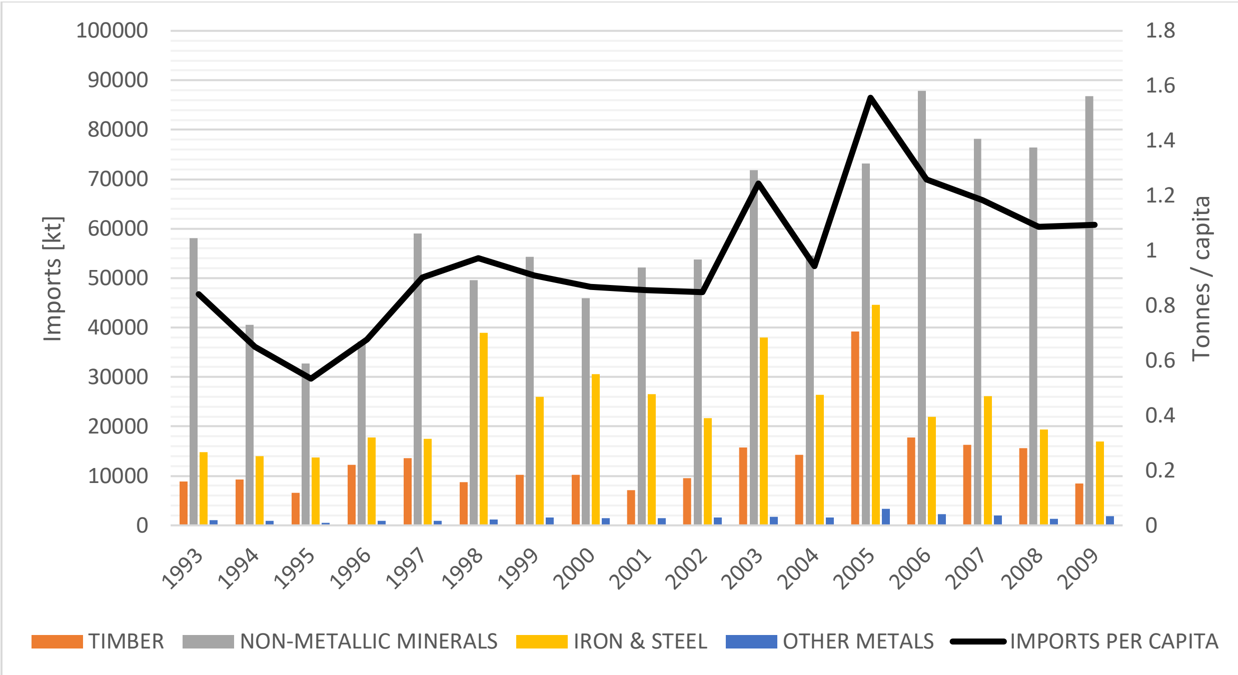


Figure 21: Imports (left axis) in Grenada from 1993 to 2009, with per capita values also plotted (right axis).

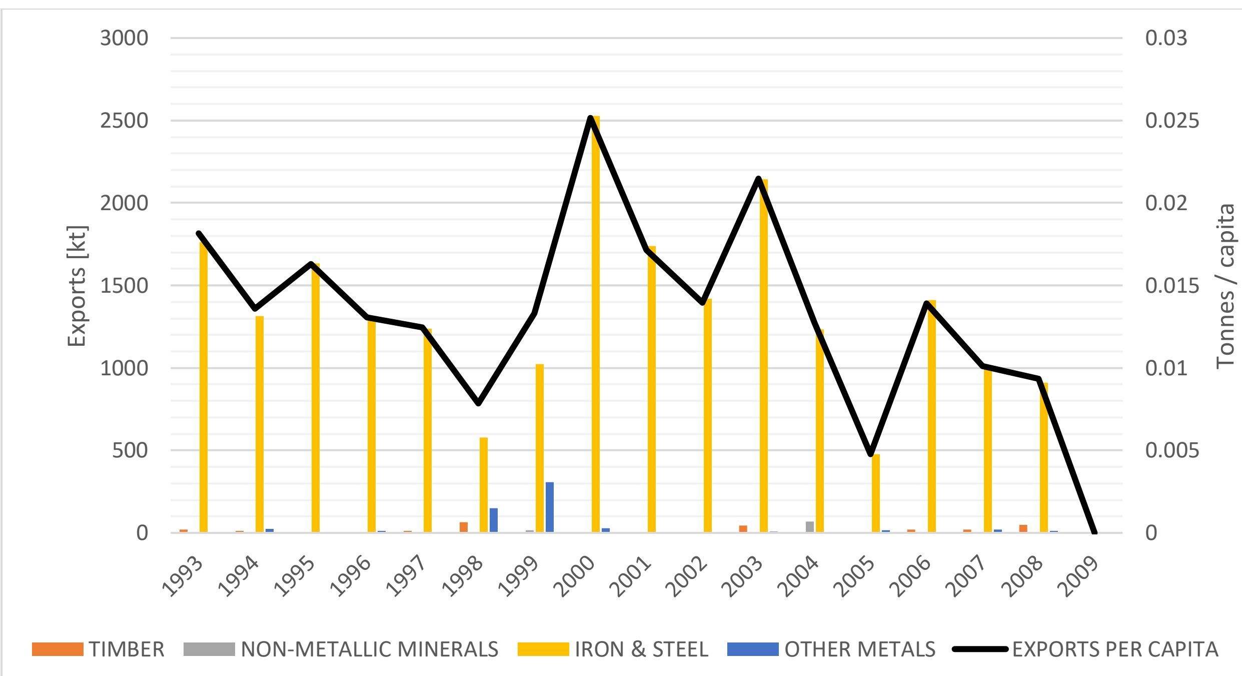


Figure 22: Exports (left axis) in Grenada from 1993 to 2009, with per capita values also plotted (right axis).

4.2.3 Physical trade balance (PTB)

Aside from sand and gravel, Grenada's construction industry completely relies on imports. Figure 23 provides Grenada's PTB disaggregated into four material categories: timber, non-metallic minerals, iron & steel, and other metals. PTB ranges from 0.5 tonnes/capita in 1995 up to 1.6 tonnes/capita in 2005, the year following Hurricane Ivan. In terms of the total share of PTB between 1993 and 2009 (see Figure 24), 61.2% was non-metallic minerals, 23.8% was iron & steel, 13.5% timber and 1.5% were other metals. The large share of non-metallic minerals is primarily due to the fact that cement is not produced domestically but must be imported for the construction end-uses discussed in the previous section.

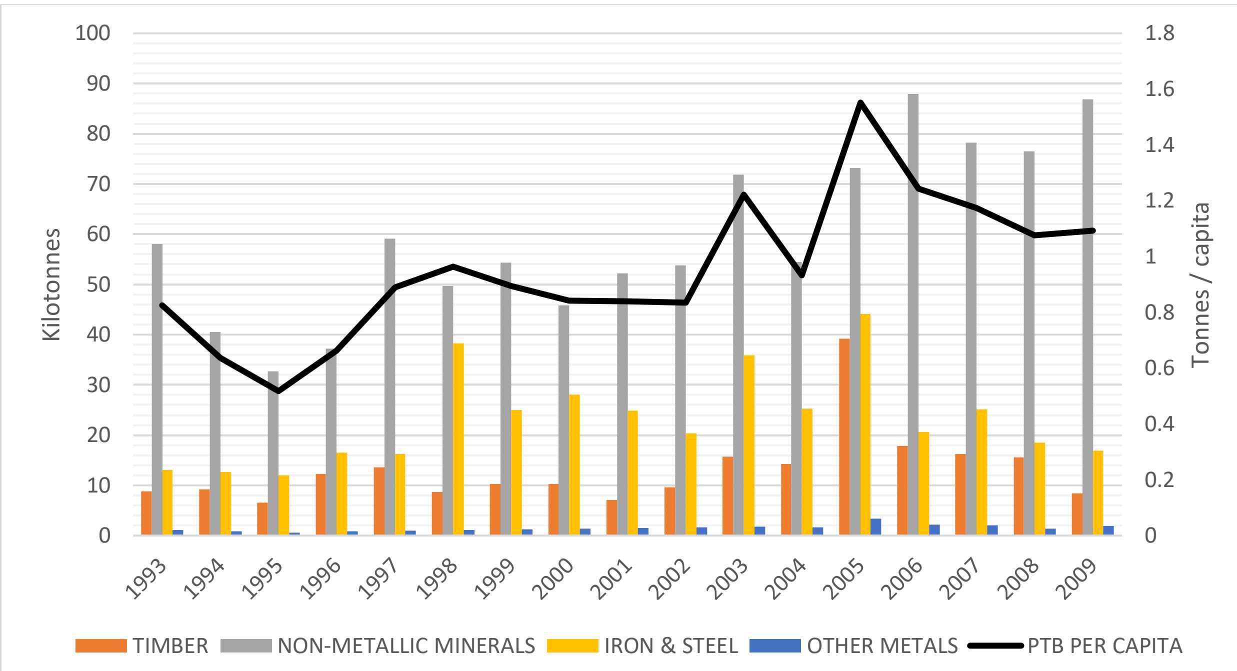


Figure 23: Physical trade balance (left axis) in Grenada from 1993 to 2009, with per capita values also plotted (right axis).

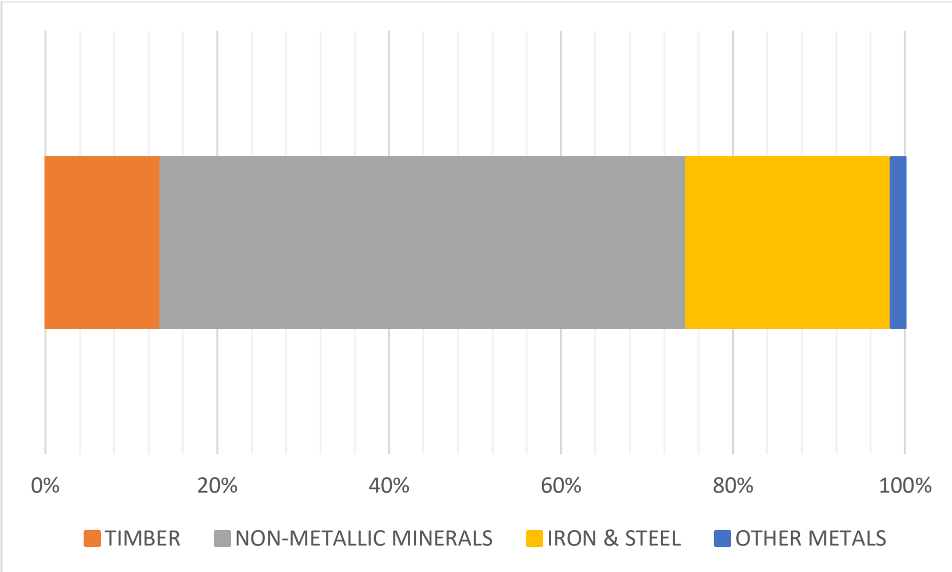


Figure 24: Breakdown of the total physical trade balance by material category in Grenada over the period of 1993 to 2009.

4.2.4 Domestic material consumption (DMC)

Domestic material consumption, shown in Figure 25, is the sum of all DE and PTB for construction materials. Across all years between 1993 and 2009, non-metallic minerals dominate the accounts due to their high density and the large volumes required in construction. DMC ranges from 2.9 to 6.6 tonnes/capita, starting out at 485 kt in 1993 versus 514 kt in 2009.

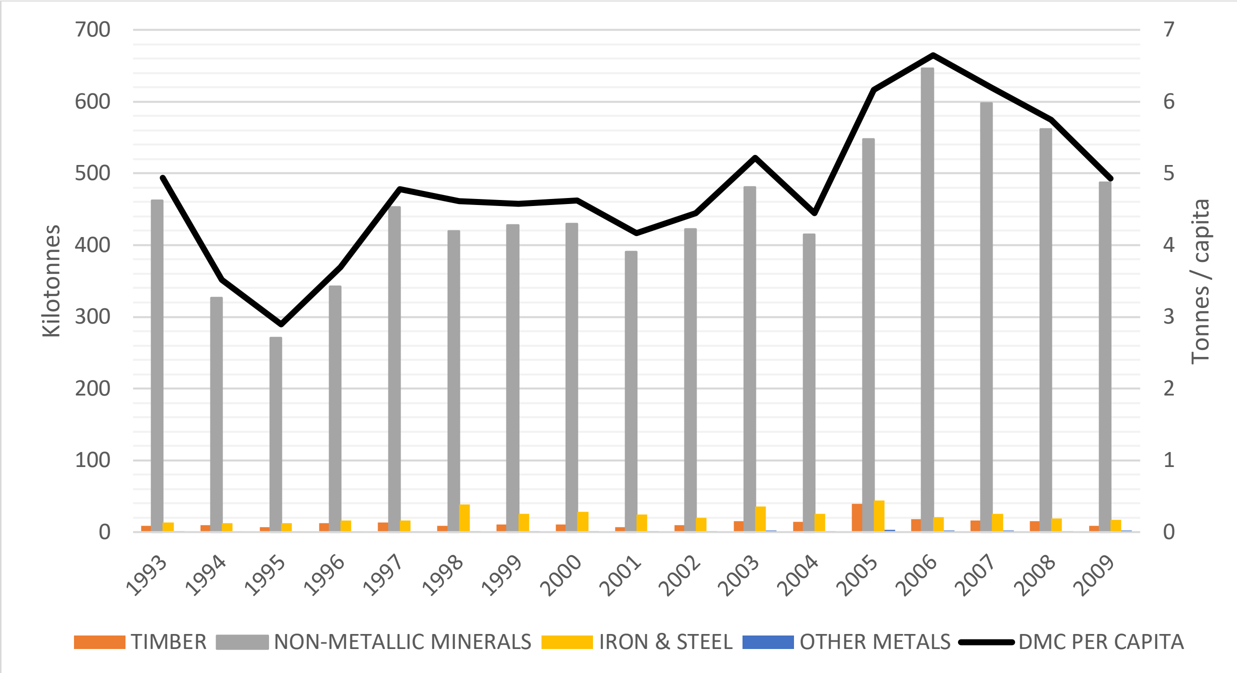


Figure 25: Domestic material consumption (left axis) in Grenada from 1993 to 2009, with per capita values also plotted (right axis).

4.2.5 Gross addition to stock (GAS)

GAS is calculated from the DMC by accounting for processing and manufacturing losses, and thus follows the same trends as the DMC indicator in this study. Figure 26 shows the aggregated GAS for 1993 to 2009, broken down to show the relative contributions from trade and domestic extraction. 6,928 kt (6.8 Mt) of construction materials were added to stock over this time period (see Figure 27 for a breakdown by material type). GAS per capita ranges from 2.4 tonnes/capita to 5.5 tonnes/capita, and the average value over this time period is 4.0 tonnes/capita. Domestic extraction on average made up 80.3% of GAS; however, this does not tell the whole story, as Figure 28 shows that over this time period 92.6% of the GAS was non-metallic minerals (which are the only construction material domestically produced) compared to 4.7% iron & steel, 2.3% timber, and 0.3% other metals. Therefore, while DE contributes a large amount of the total GAS, it is very important to note that it does not satisfy the variety of materials needed by the construction industry. Additionally, since non-metallic minerals are added to stock on an order of magnitude larger than the other material categories, its annual trends are the only ones visible on a total GAS chart. To remedy this, GAS for each category was plotted separately in Figure 23, that highlight the trends occurring for different materials year-by-year.

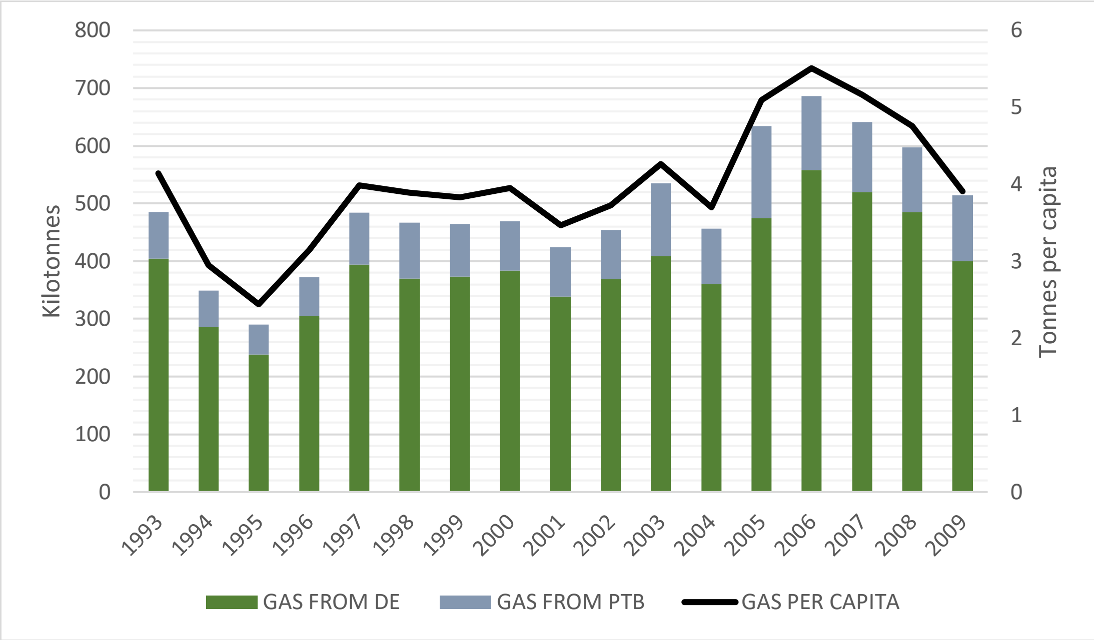


Figure 26: Gross addition to stock, broken down by contributions from DE and PTB (left axis) in Grenada from 1993 to 2009, with per capita values also plotted (right axis).

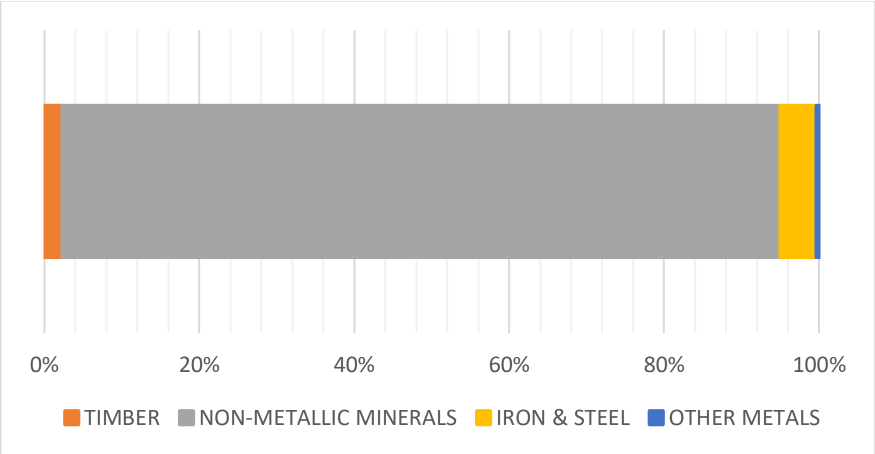


Figure 27: Breakdown of gross addition to stock by material category in Grenada over the period of 1993 to 2009.

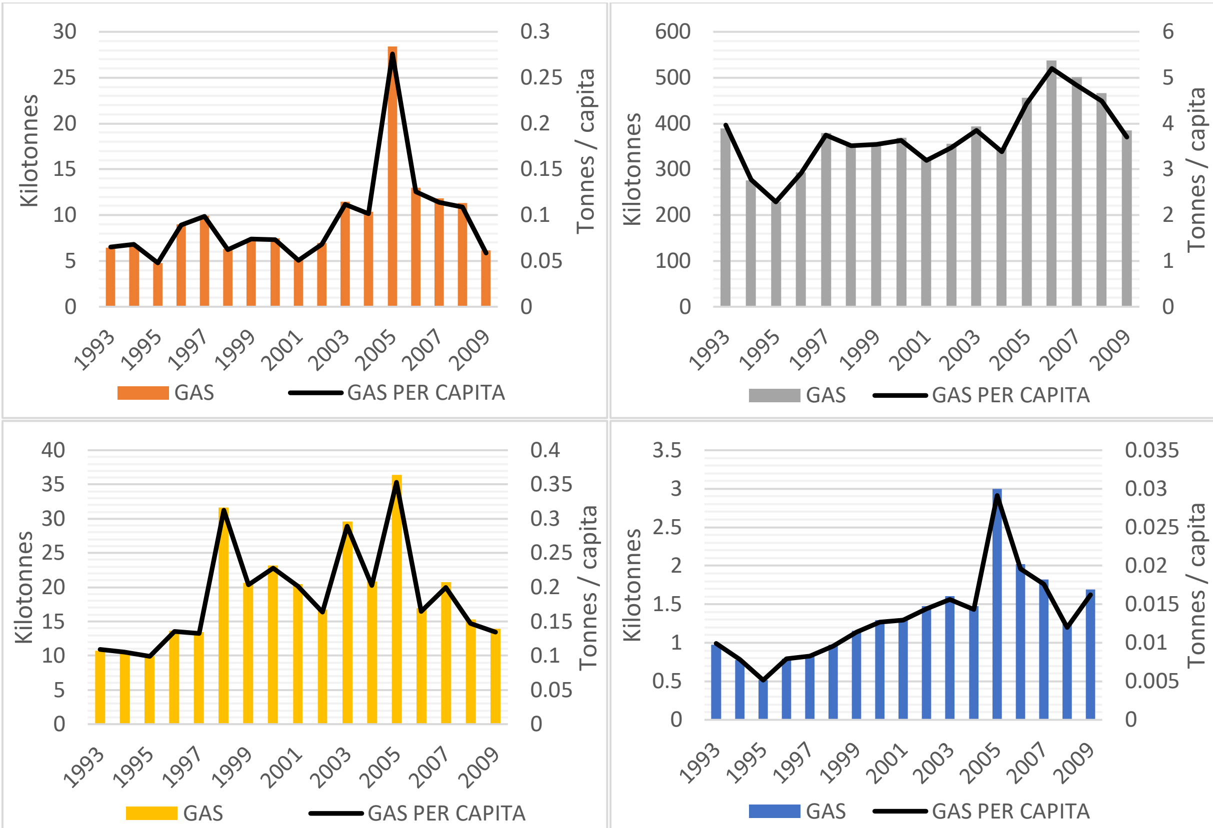


Figure 28: Gross addition to stock in Grenada from 1993 to 2009, plotted separately for four material categories: timber (top left), non-metallic minerals (top right), iron & steel (bottom left), and other metals (bottom right). Absolute values are shown (left axis), with per capita values also plotted (right axis). Note the different scales for each graph.

These material-specific GAS indicators show a couple of interesting trends. Beginning in the late 1990s, iron & steel GAS becomes quite volatile; and in 2005, GAS for both timber and other metals experience a noticeable spike. The latter coincides with the year following Hurricane Ivan, and suggests the MFA for construction materials can in fact provide some insight into this natural disaster. These impacts are discussed in the following section.

4.3 Impacts due to disasters and climate change

This section begins with a closer investigation of the spike in material flows Grenada experienced following Hurricane Ivan. It then shifts to an analysis of different disaster related scenarios and how they would impact the 2014 model of building material stock in Grenada. Firstly, hurricane scenarios are examined; and secondly, the potential effects of sea-level rise are explored.

4.3.1 Hurricane Ivan (2004)

On September 7, 2004, Hurricane Ivan passed approximately 10 kilometers south of Grenada. Sustained wind speeds were at least 190 km/h and gusts reached over 230 km/h (OECS 2004). damaged 89% of homes in Grenada, with 30% completely destroyed (The World Bank, 2005). The hurricane also impacted social services infrastructure, as the majority of public health and education buildings were severely damaged. Within the tourist industry, 70% of hotel infrastructure was unusable (The World Bank, 2005). This subsection first continues to look into the MFA results to consider Ivan's impact on material flows, and then considers "future" scenarios of material stock losses.

4.3.1.1 Influence on material flows

As discussed in Section 4.2.5 of the MFA results, there is a noticeable spike in GAS for both timber and other metals. Figure 29 shows the growth rates of GAS for both of the materials. In 2005, timber GAS per capita spikes by 172% while other metals GAS per capita spikes by 103% (compared to averages of 11% and 8%, respectively, between 1993 and 2009). Even compared to the average fluctuation in GAS, these results suggest the scale of rebuilding efforts are seen from the MFA.

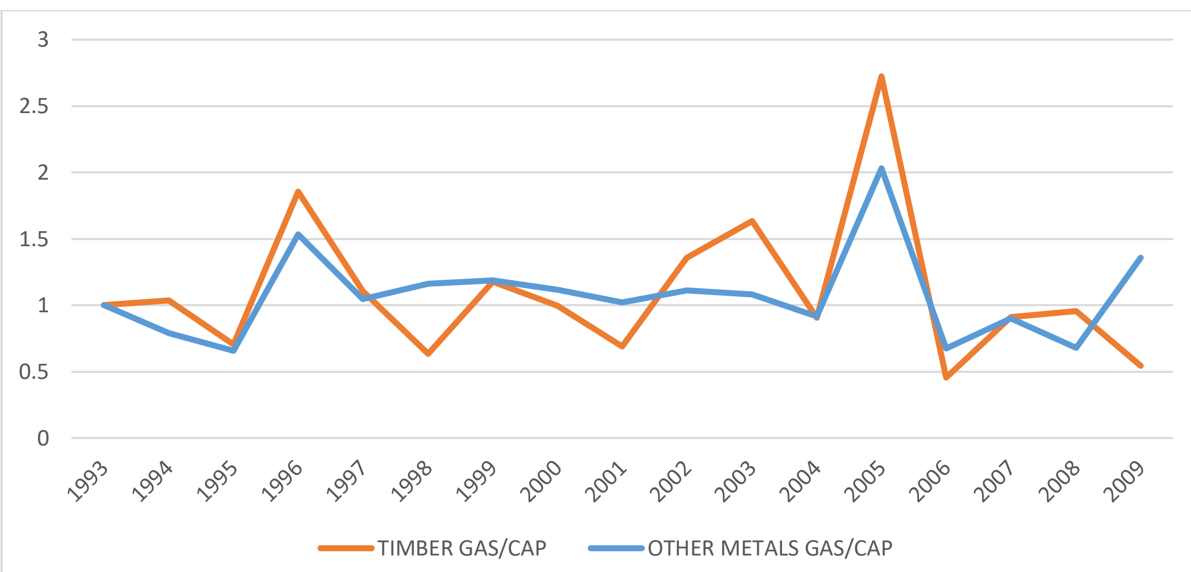


Figure 29: Growth rates of GAS per capita for timber and other metals. Normalized to 1993 = 1.

The notable increase in timber flows are especially interesting considering on-site reports of Hurricane Ivan damages from the World Bank. Figure 30 below shows an overview of damage levels experienced by homes across Grenada from Hurricane Ivan. Of note is the damage scale used by the World Bank (2004); which primarily rates the damages to the roof of homes. Based on the results of the building material stock analysis, much of Grenada's timber stock is located in the roof and thus was highly vulnerable to the powerful cyclone winds during Ivan. Based on this observation and GAS trends for timber, the next section considers the impacts of Ivan on the 2014 stock of timber in buildings.

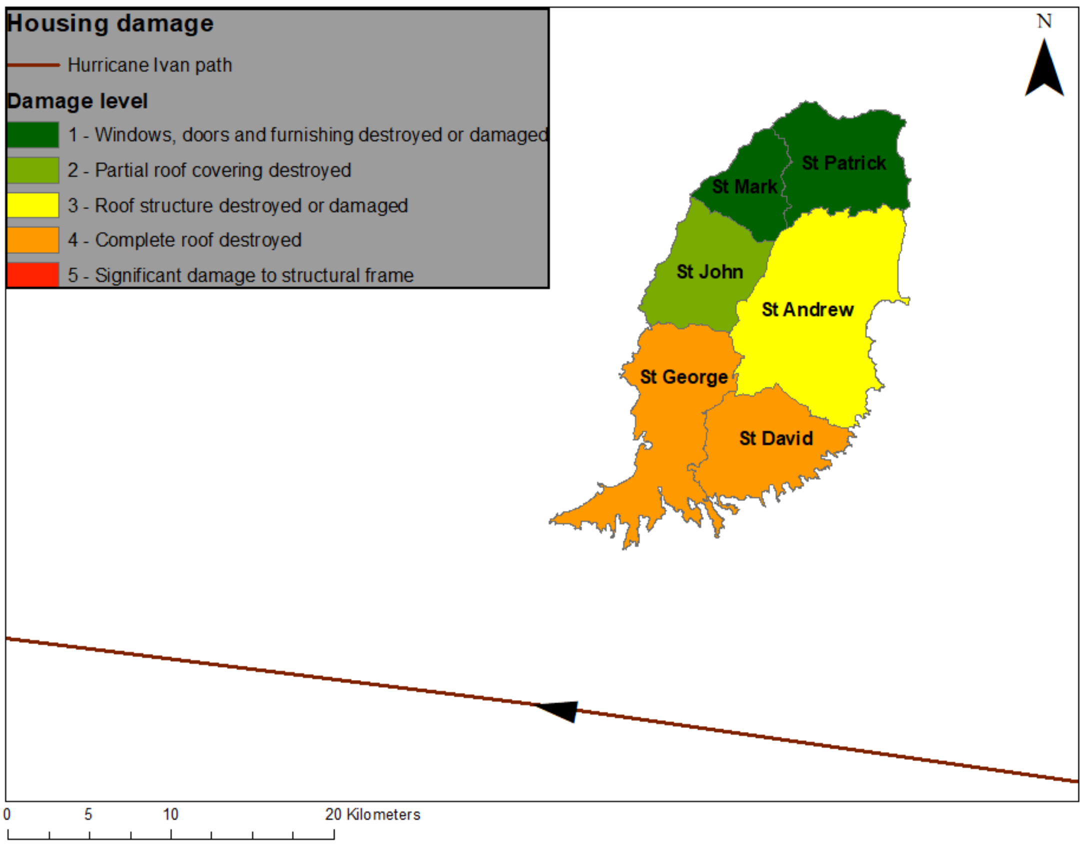


Figure 30: Most prevalent damage level to homes in each of Grenada's main-island parishes. Data sourced from The World Bank (2004).

4.3.2 Future scenarios

4.3.2.1 Extreme weather and the building stock

As described in Methodology Section 3.3.1, three different "Loss scenarios" of varying severity were considered for an Ivan-II event (i.e. were the identical storm occur again) using the damage levels and severity assumptions in Table 6 and Table 7. Timber stock loss is mapped for the three different scenarios in absolute amounts in Figure 31 and per unit area amounts in Figure 32. A summary of total timber stock lost can be found in Table 14. As can be seen on the maps the majority of damages, in absolute terms and by area density, are concentrated to the southwestern part of the island. The reason for this is two-fold: Firstly, material stocks have the highest concentrations in this part of the island; and secondly, the eye of Hurricane Ivan (and hence the hypothetical Ivan-II) passed nearest to this part of the island, as shown in Figure 30.

Table 14: Total timber losses from material stock in 2014 building for three severity levels of an "Ivan-II" event.

Loss scenario	Total timber stock lost from buildings
Low	135 kilotonnes
Mid	173 kilotonnes
High	216 kilotonnes

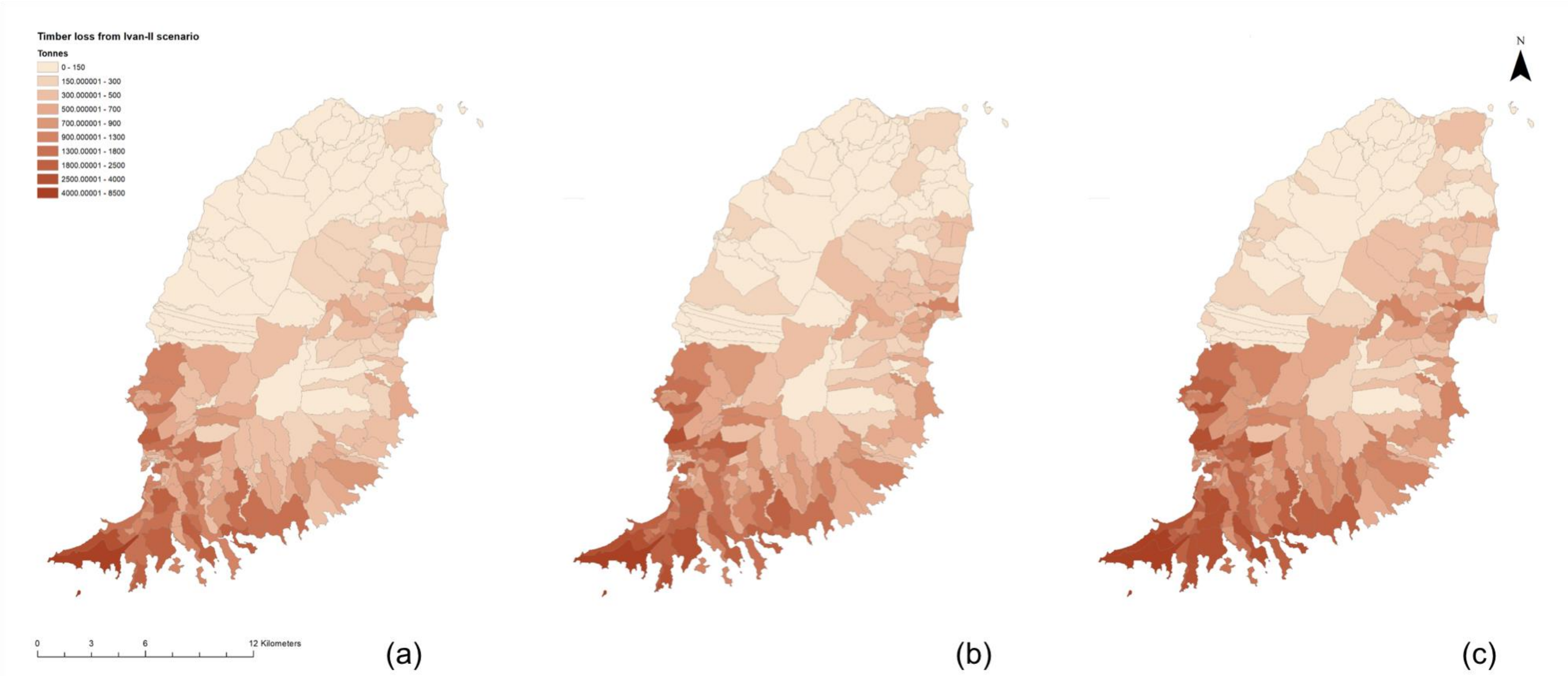


Figure 31: Absolute timber stock losses in an "Ivan-II" scenario from 2014 buildings by census enumeration district. (a) Low-loss scenario; (b) Mid-loss scenario; (c) High-loss scenario.

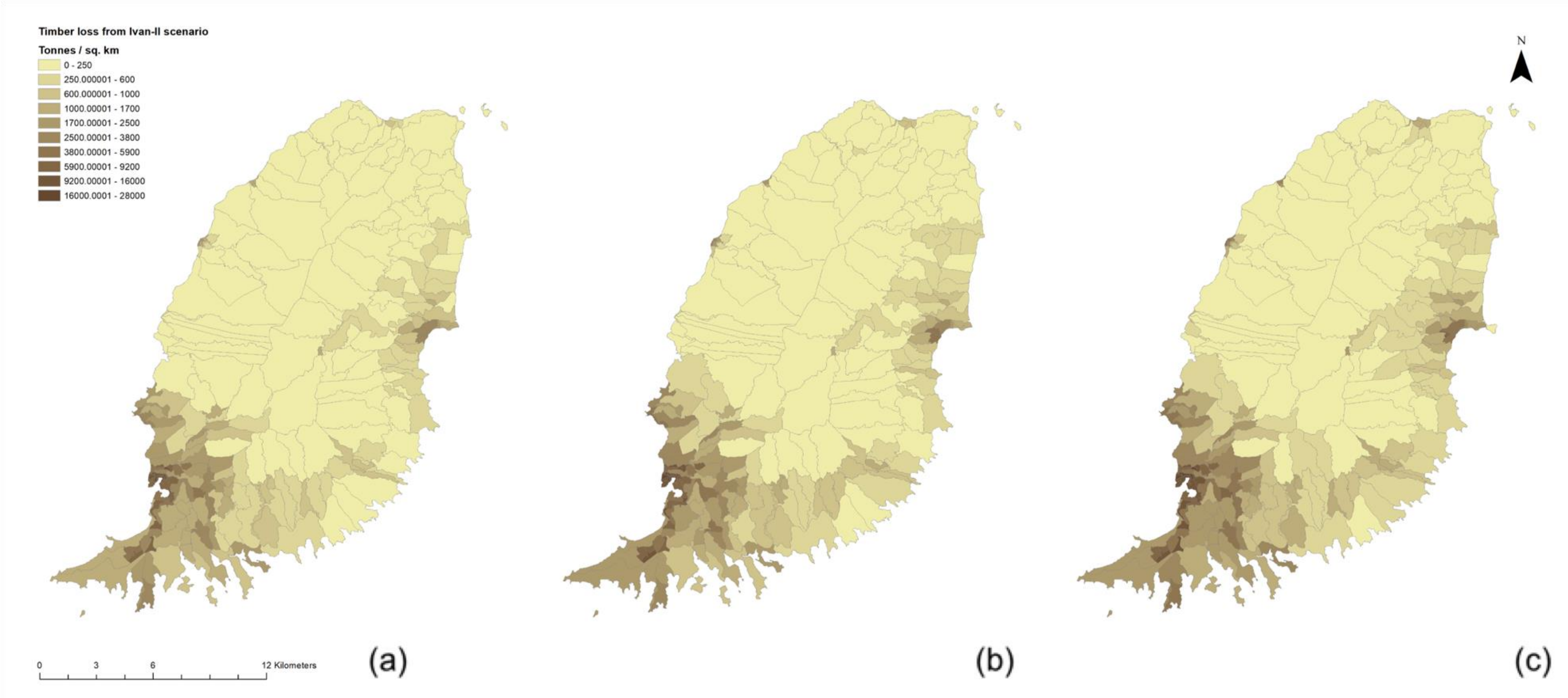


Figure 32: Area density of timber stock losses from 2014 buildings by census enumeration district. (a) Low-loss scenario; (b) Mid-loss scenario; (c) High-loss scenario.

4.3.2.2 Sea-level rise

The results of the sea-level rise (SLR) scenario analysis, summarized in Table 15, show that in absolute terms the Tourism sector buildings are most exposed to 1m, 2m and 3m scenarios, with 421 kt, 466 kt and 520 kt of material exposed respectively to rising sea levels. However, considering the results in terms of percentage of total stock in that use-type, 26-33% of Tourism building materials are at risk compared to 67-86% in the Cultural category, and 62-68% for Transportation. Relative to other use-types, Residential buildings are least at risk, with 2-5% of the total stock in this category exposed to SLR. A map of buildings exposed in the three scenarios is shown for the St. George's test area in Figure 33. In this map it can be seen that much of the inner harbour in St. George's is exposed to a 1m scenario, which is considered highly likely before the turn of the century. The lack of exposed buildings only 100 to 200 meters inland illustrates the rapid increase in elevation away from the ocean, as much of the interior of the main island is mountainous.

Table 15: Total material stock exposed (absolute value and percentage) for each building use-type for the three sea-level rise (SLR) scenarios. Units: kt.

SLR scenario:	**1m**		**2m**		**3m**	
Use-type	**MS exposed**	**% of use-type MS**	**MS exposed**	**% of use-type MS**	**MS exposed**	**% of use-type MS**
Institutional	169	25%	233	35%	252	37%
Commercial/Industrial	250	19%	410	30%	495	37%
Residential	173	2%	290	4%	397	5%
Tourism	421	26%	466	29%	520	33%
Cultural	78	67%	101	86%	102	86%
Transportation	140	62%	153	68%	154	68%

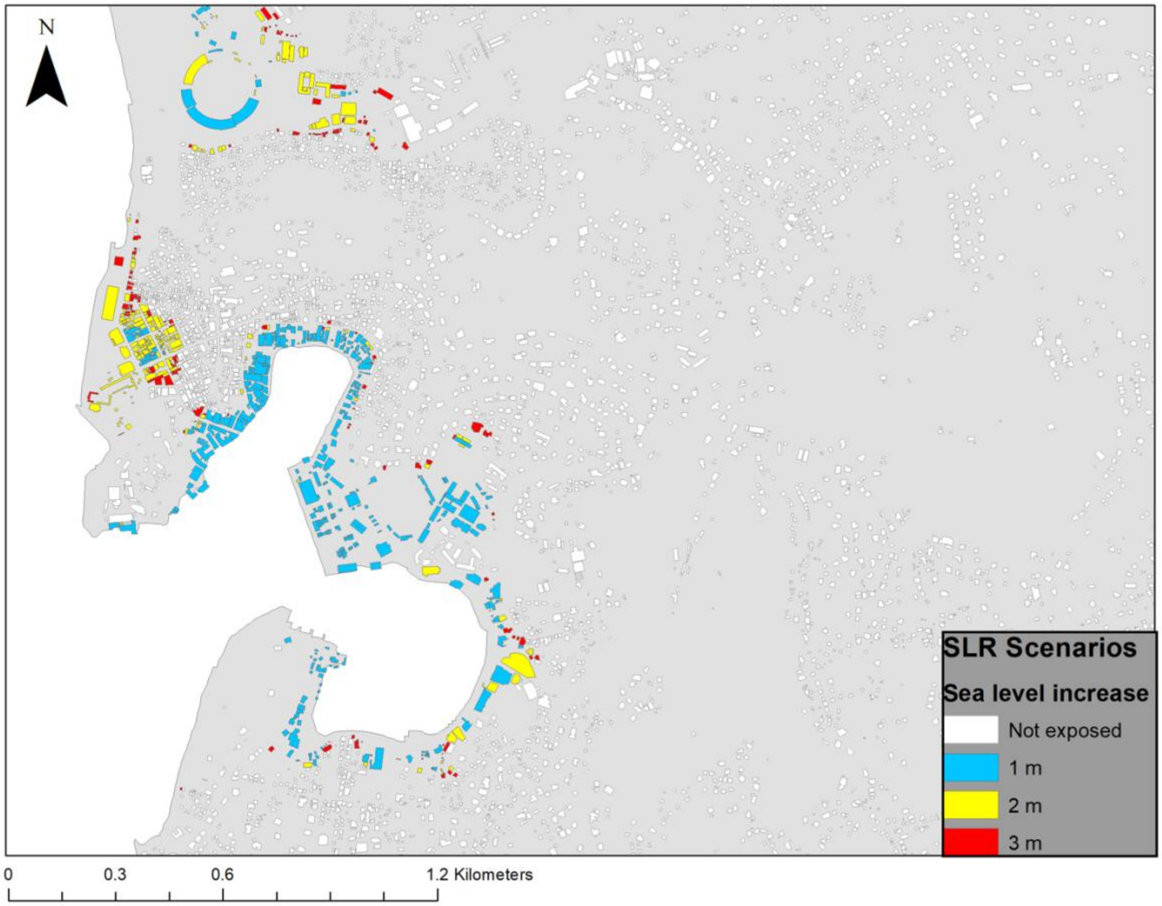


Figure 33: Buildings exposed to sea-level rise under 1-meter, 2-meter and 3-meter scenarios.

5 Discussion & Conclusion

This section concludes the thesis with a discussion of the key results, and how they address the main research questions (Section 1.2). Also considered is what the answers to these questions mean for building resilience to climate change and disasters in Grenada. Limitations of the research and avenues of future work are also discussed, followed by a concluding statement for the work as a whole.

5.1 Grenada's material stocks and flows

Grenada's MS in buildings is estimated at 112 t/cap in 2014. A current estimate by Mesta, Kahhat, and Santa-Cruz (2018) for the city of Chiclayo, Peru estimates MS in buildings at 55 t/cap (47 t/cap in 2007), and Tanikawa & Hashimoto (2009) have estimated MS in 2004 buildings in Salford Quays, UK and Wakayama, Japan to be 78 t/cap and 216 t/cap, respectively. Past research has also studied residential buildings specifically: 139 t/cap in residential buildings in Vienna, Austria (Kleemann et al. 2016) compares to 74 t/cap for Grenada. It should be noted that all studies compared here are urban areas, while Grenada's estimates include the entire country. Specifically, for non-metallic minerals in residential buildings, Weidenhofer et al. (2015) estimate up to 72 t/cap in the EU-25 while this research calculated 70 t/cap for Grenada.

As a comparison with the larger Caribbean nation, Cuba, Grenada's 4.1 t/cap extraction of nonmetallic minerals in 1993 compares to only 1.7 t/cap in Cuba (Eisenhut 2009). A decade later in 2003, mineral extraction in Grenada was slightly lower at 4.0 t/cap, but still twice as much as Cuba at 2.0 t/cap. However, Grenada's 1993-2009 average DE per capita (3.8 t/cap) is lower than that for Latin America & the Caribbean (4.6 t/cap) (WU, 2014). As seen from the breakdown of end-uses for these minerals, much of this extraction is used to meet the demand for concrete production; this result appears to be very much in line with the results indicating a large share (85%) of concrete in the building material stock in 2014. However, the fact that timber, iron and steel, and other metals must be imported means Grenada is dependent on external markets for its other essential building materials.

The time-series of GAS shows some instability in per capita levels even though population showed steady growth of 9% from 1993 to 2009. This is particularly noticeable for iron and steel beginning in 1997. One reason for this could be due to the absolute size of the Grenadian economy (USD $1.1 billion GDP in 2017), as a large new construction project (e.g. a new private-sector beach resort) will have substantial material requirements in comparison to years with no major projects underway in the country. In larger economies there is a sort of 'baseline' of construction activity in each year – for example, Fishman et al. (2014a) estimate Japan's GAS at nearly 1 billion tons per year from 1970 to 2000 – in which a single new project will not cause noticeable growth in per capita levels. As a result, while analysis of the GAS accounts of large nations puts a focus on environment pressures of population and economic trends, for a small island nation these accounts might be able to highlight the pressures of specific expenditures, especially as infrastructure is being expanded for a growing tourism industry. An important consideration also comes from the discussion of circularity of construction materials: will outflows of material stocks "accumulate" in different sectors if recycled, and could this result in some disparity of who sees the benefits?

In addition to the "what and where" of material stocks, this research has also informed the "services" aspect. Large portions of the building material stock provide services for foreign visitors (such as beach resorts and St. George's University), and are expected to expand in the future. Expansion of these stocks may grow faster relative to local populations, and thus per capita levels of material stock could rise. Expansion of these stocks and services will result in job growth in the construction sector, which in the short-term makes progress towards Sustainable Development Goal (SDG) #8 – Decent Work and Economic Growth; however, with limited land area and coastline, this may not be sustainable long-term for the country. Additionally, the growth of luxurious tourist destinations may tie these stocks to excessive material and energy flows, a concern related to SDG #12 – Responsible Consumption and Production.

5.1.1 Insights from spatial distribution of buildings

Spatial distribution maps of the material stock in buildings highlights the concentration of Grenada's population and economic activity in coastal areas of the island. There are some intuitive explanations for this pattern: using this low-lying, less mountainous land in these areas is easier for development of buildings and infrastructure and is more accessible from the ports of entry through which construction materials and population are flowing. However, this isn't to say concentrations of material stock are absent from the interior of the island, as the elongated strips of material stocks reflect the presence of transport infrastructure and economic activity inland. For example, an interior roadway connects the Town of St. George's and Grenville (Grenada's largest cities) on opposite sides of the island; several small rural villages reside along this roadway. Additionally, much of Grenada's agriculture industry operates in the interior to the north.

The spatial distribution provided in this research can serve as a valuable tool for planners as it provides locations and amounts of materials that will eventually be output from stock at construction and demolition waste (Mesta, Kahhat, and Santa-Cruz 2018), providing opportunities to prepare recycling or downcycling procedures to improve circularity in the construction industry (Augiseau and Barles 2017); by doing so, Grenada could benefit from urban mining and reduce reliance on imports of materials not available domestically. It should be noted, however, that total self-sufficiency may not be a realistic goal, as materials become degraded over time and must be down-cycled to different construction uses. If cement cannot be produced domestically (requiring limestone), new construction using concrete will still rely on foreign imports. Nonetheless, before decision-makers in policy and industry can take steps toward urban mining, better information regarding the survivability of buildings and infrastructure is needed to gain temporal understanding of construction and demolition waste outflows.

5.2 Leveraging the stock – flow perspective to build resilience

The MFA results highlight the need to strike a balance between resilience, sustainability, and environmental burdens. Grenada has imported or domestically extracted 6.9 Mt of construction materials in 16 years (1993-2009), equivalent to nearly half the construction materials stocked in its buildings in 2014 (12 Mt). This high flow-to-stock ratio suggests high overall turnover of the stock, although the figures are not fully comparable because it is hard to ascertain to what end the GAS were used without further data, especially of the materials stocked in non-building construction and of construction & demolition waste generation. This high turnover in demand for construction materials is not sustainable, and its causes need to be better understood.

Hurricane Ivan was identified as a specific cataclysm with significant increases in GAS of timber and other metals in 2005, providing empirical evidence of a socioeconomic system reproducing its stocks (and restoring services) following a disaster. Interestingly both timber and other metals experience a decrease in GAS in 2006, suggesting there was a potential oversupply of material imported in 2005 in reaction to recovery efforts. However, in parallel to natural disasters, ongoing development in Grenada is likely to be driving rapid turnover of materials because older buildings may be now of poor quality and the need to increase the provision of services as the country develops (Cai et al. 2015).

While these historical data provide an interesting picture of Grenada's vulnerability in the past, the focus now is to improve the nation's resilience for future events related to climate change. New construction should be built not only to resist natural disasters, but also be resilient to socio-economic changes by providing and accommodating future socio-economic needs and services while minimizing material flows for maintenance and expansion. In addition, appropriate spatial planning in the case of Grenada becomes imperative, as well as designs of buildings to enable recoverability of materials for reuse. Strategies for resilient infrastructure, and developing the industrial processes for material recoverability, will help Grenada progress toward SDG #9 – Industry, Innovation and Infrastructure. The analysis of potential stock loss scenarios, in addition to contributing as a novel application of material stock accounts, is meant to be a relevant set of results for policy makers. This research addresses two key strategies outlined in the *National Climate Change Policy for Grenada, Carriacou and Petite Martinique (2017-2021)* (Government of Grenada 2017): i) to strengthen statistical capacity, and ii) to assess vulnerability of assets in Grenada.

The three hurricane Ivan-II scenarios for the 2014 building stock estimate between 135 kt and 216 kt of lost timber; however, there is some reason to suggest the Mid- or Low-Loss scenarios are more realistic, as Grenadians have adapted their construction of roofs since Ivan to improve reinforcement (Finlay 2010). There are also important lessons from construction trends in the tourism sector; consultation with an expert building new accommodation units in 2017 emphasized the importance of moving away from timber and sheet steel roofs when possible, and rather using concrete. As of 2011, 96.5% of homes in Grenada used galvanized steel roofing

(Central Statistics Office, 2011). Additionally, it was observed in 2004 after Ivan that older, less-resilient units were in fact the least damaged because they were sheltered by trees and other new buildings. The use of windbreaks could be a key strategy for improved building resilience and thus decreasing material stock losses from buildings. 'Natural' tree windbreaks have been proposed for use in protecting NASA facilities from hurricanes in Florida (Hyater-Adams and DeYoung 2012).

Following Ivan, many buildings in the Town of St. George's were abandoned and remain unused to this day. It was unclear from the CHARIM 2014 building footprints whether these abandoned buildings were included; if they were, and as a result were part of calculations in this methodology, a small portion of the building material stock is in fact not currently in-use. Future on-site investigation could address the question of what amount of abandoned material stock in Grenada remains from Hurricane Ivan. This could further illuminate how recovery from a disaster is affecting material stocks, flows and services following a disaster, as research has discovered high rates of building abandonment following a hurricane (Zhang and Peacock 2009).

Three sea-level rise (SLR) scenarios (1m, 2m and 3m) were provided in this research. While some building use-type categories saw a steady rise in MS exposed as the severity of the scenario increased, others were "immediately" at risk in the 1m scenario, an alarming result given the likelihood of 1m SLR by 2100 (Simpson et al., 2010). For example, Cultural and Transportation use-types have 67% and 62% of MS exposed, respectively. This result can be explained: The Cultural MS at risk is mostly contained in the large National Cricket Stadium, located in a low-lying area of St. George's. In the Transportation category, the MS at risk is located in buildings at the port (which must be at sea-level). In absolute amounts of MS the largest concern is the Tourism sector, with 421 kt to 520 kt of MS exposed to sea-level rise (ranging from 26% to 33% of all Tourism MS). This highlights the importance of diversifying tourism away from beach resorts and toward more inland accommodations and cultural attractions, which could also have the added benefit of locating MS in areas less vulnerable to hurricanes (e.g. storm surges, high winds).

These considerations discussed here have some other important implications: the potential threats of extreme weather to the MS in buildings means that recovery efforts are relying on imports of timber, and thus ports of entry must be open and accessible. For waste management, the results of this research could be used as a starting point for improving resource recoverability planning, lessening the pressure of importing goods and reducing waste deposited to landfills. In the case of sea-level rise, the question of coastal pollution arises – are there harmful stocks of materials that must be managed to avoid threats public health and ecosystems? While this study has focused on the 'main' materials of construction, countless other materials are used in buildings that could be considered; some of which may be hazardous like lead and asbestos. If proportions relative to these main materials in Grenadian buildings is known, then the present results could be used as indicators of potential pollutants.

5.3 Limitations & future work

As discussed in the Methodology, the characterization of building footprints required an iterative process to develop an appropriate system for assigning occupancy classes. This classification system was developed remotely, using secondary imaging sources and field work photos and observations. In an ideal situation, a second round of field work could be used to conduct on-site surveys to validate the system and make necessary adjustments. Another potential limitation of the methods used to calculate MS come from determining gross floor area (GFA): since the height for each building footprint was not known, average height assumptions were assigned to each occupancy class. While these were not "blind" assumptions, having an accurate account of height for every individual building would certainly improve the GFA calculation and ultimately improve accuracy of the MS account. One solution is through remote sensing data: the Grenadian government conducted a LiDAR survey of the country in November 2017 (NOW Grenada 2017) through the Regional Disaster Vulnerability Reduction Project (The World Bank 2011). If made available, building heights could be extracted from this survey data.

The tourism industry in Grenada, as a SIDS case study, has interesting research potential moving forward. While material and energy flows have already been examined (Telesford, 2014; Telesford & Strachan, 2017), further investigation of the material stock could build the full material stock-flow-service nexus perspective for this sector. The proprietary nature of information regarding beach resort facilities and planning made collecting data related to material intensity difficult. Resort architecture is often very unique and ornamental, and thus it is possible that defining separate material intensity typologies could be from other Grenadian buildings could be beneficial. For example, one expert that was interviewed discussed the fact that during resort construction, procurement of materials is done directly with international partners, and generally higher quality materials are used than in the rest Grenada's buildings. This could indicate that the growing tourism sector may not always be compatible with circular loops of materials from the rest of the economy.

While the MFA results in this thesis have shown annual inflows to the material stock with the GAS indicator, this flow-based perspective of the material stock could be further developed into an account of the net addition to stock (NAS) (e.g., Fishman et al., 2014). NAS provides a fuller time-series account of how the material stock is changing in a socioeconomic system, and if the existing stock prior to the study period can be estimated, a full MS account can be calculated and compared with stock-driven analysis. The scope of the stock-driven MS account could also be expanded to the other main containers of construction materials including roadways, ports and utilities infrastructure (e.g. pipelines; see Lwin et al. 2017).

Determining NAS requires a method to model outflows from the material stock due to demolitions and, of course, events such as disasters. Different approaches can be taken to do this (also outlined in the Literature Review), and data requirements might include: construction waste data; civil infrastructure maintenance schedules and material requirements; statistics on building/infrastructure age and demolitions; and general practices regarding demolitions, e.g. what happens to subsurface foundations. Residential building age is available in the census; however, these other data requirements were difficult to address during field work for this thesis. Nonetheless, future field work to conduct on-site surveys and consultation with industry experts could potentially address these data gaps.

5.4 Conclusion

This is a novel study of material stocks and flows in Grenada, and the first material stock account in the Caribbean region. It offers both a quantitative and spatial view of how a small island developing state (SIDS) organizes its stock of construction materials, how that stock is built up using international trade and domestic extraction, and how both of these are impacted in the face of extreme weather and sea-level rise. While the threat of disasters and climate change are understood by policy-makers, this research communicates the biophysical scale of some of these challenges and their implications.

In addition to the empirical contribution, this thesis also makes a methodological contribution. Material stock studies vary in scope and purpose, and thus have a range of approaches and data requirements to meet their goals. Given the data constraints of a SIDS, this study has developed a GIS-based method to characterize buildings in the country by the services they provide and the construction materials they contain. This methodology has the potential to be used in other Caribbean case studies and allow national results to be compared in the region, whether it is for constructing similar natural disaster scenarios or to compare the service aspect of material stocks among SIDS.

In line with other recent works, this research has also shown the valuable contribution industrial ecology tools can make to disaster risk information, for events such as earthquakes, hurricanes and sea-level rise due to climate change in the 21st century. The results not only help in planning for resilience, but also provide indication of the environmental pressures from natural disaster recovery and how resilience to these events is linked to global resource use patterns.

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Appendices

A. Grenada geodatabase

Table A1: Metadata for the Grenada geodatabase. Coordinate system: WGS 84; Datum: World Geodetic System 1984; Prime Meridian: Greenwich; Angular: Degree.

Description	FileName	Tags	Summary of Data	Source/Credits/Link	Any Use Limitations (sensitive information)	Data type(s)	Attributes	Coordinate System	Resolution	Details	Units	Date of Publication/Creation (in Description in ArcGIS)	Notes
Airports and Seaports	transportation_ports	airports, seaports, area, transportation	Seaports and Airport area within Grenada	Caribbean Handbook on Risk Information Management (CHARIM); the website also has a set of maps that use these layers http://charim-geonode.net/people/profile/grenada/?content=layers	No	Feature class - Polygon	Airport or Seaport, Shape Area	GCS: WGS 84 Datum: World Geodetic System 1984	n.g.	Vector		April 4, 2016	
Hurricane shelters	hurricane_shelters	hurricane shelters, NADMA, CHARIM	Hurricane shelters generated from a list of shelters by NADMA (National Disaster Management Agency-Grenada)	Caribbean Handbook on Risk Information Management (CHARIM); the website also has a set of maps that use these layers http://charim-geonode.net/people/profile/grenada/?content=layers	No	Feature class - points	Shelters name, location, type (ie. school, community centre, church, etc), lat, long	GCS: WGS 84 Datum: World Geodetic System 1984	n.g.	Vector		April 4, 2016	
Landslide susceptibility	landslide_susceptibility_2016	landslides, landslide susceptibility, 3 scales: low, moderate, and high susceptibility	Landslide susceptibility map generated by Cees van Westen (ITC) using a combination of statistical analysis of historical landslides (mapped from satellite images pre-and post Ivan), Spatial multi-criteria evaluation and manual editing	Caribbean Handbook on Risk Information Management (CHARIM); the website also has a set of maps that use these layers http://charim-geonode.net/people/profile/grenada/?content=layers	No	Raster feature class	3 classes: High-3, Moderate-2, Low-1		n.g.	Raster	GRAY_INDEX	April 4, 2016	
Landslide inventory	landslides_inventory	landslides, type of material, post Hurricane Ivan	This inventory was generated by Cees van Weston (ITC) as part of the CHARIM project. Based on image interpretation of post-Ivan high resolution satellite data, and more recent satellite images.	Caribbean Handbook on Risk Information Management (CHARIM); the website also has a set of maps that use these layers http://charim-geonode.net/people/profile/grenada/?content=layers	No	Feature class - polygon	area, did a slide occur in 2005, what type of slide, failure type, material types, post ivan?, post ivan type, area	GCS: WGS 84 Datum: World Geodetic System 1984	n.g.	Raster; post-Hurricane Ivan (2004)		All data displayed from 2005, post Hurricane Ivan , Published: Jan 01 2005 - June 01 2015	
Quarries and waste disposal sites	quarries_2016	Quarries, waste disposal, environment	Quarries and waste disposal sites, digitized from high resolution satellite images	Caribbean Handbook on Risk Information Management (CHARIM); the website also has a set of maps that use these layers http://charim-geonode.net/people/profile/grenada/?content=layers	No	Feature class - polygon	Quarry type, area	GCS: WGS 84 Datum: World Geodetic System 1984	n.g.	Vector		April 1, 2016	

Parish boundaries	parish_bound	parish boundaries, Grenada	Administrative units (Parishes) of Grenada	Caribbean Handbook on Risk Information Management (CHARIM); the website also has a set of maps that use these layers http://charim-geonode.net/people/profile/grenada/?content=layers	No	Feature class - polygon	Parish name, area	GCS: WGS 84 Datum: World Geodetic System 1984	n.g.	Vector; shows boundaries		published April 1, 2016 Still current	
Demographic data	ed_demographic_data_2011	demographics, census, planning, Grenada	Demographic data per enumeration district from last census, provided by the Central Statistical Office (CSO), Ministry of Finance, government of Grenada.	Caribbean Handbook on Risk Information Management (CHARIM); the website also has a set of maps that use these layers http://charim-geonode.net/people/profile/grenada/?content=layers	No	Feature class - polygon	Enumeration district ID, number of households (Hh), pop. of ages 0-4, pop. of ages 5-64, pop. of ages 65+, male pop., female pop., total pop.	GCS: WGS 84 Datum: World Geodetic System 1984	Census enumeration districts	Vector; population	# people	per last census - 2011	
Grenada rivers	rivers_2016	Rivers, grenada	Rivers from the Ministry of Agriculture Grenada database	Caribbean Handbook on Risk Information Management (CHARIM); the website also has a set of maps that use these layers http://charim-geonode.net/people/profile/grenada/?content=layers	No	Feature class - line	River identity, nodes, length	GCS: WGS 84 Datum: World Geodetic System 1984	n.g.	Vector; line		May-16	
Road network	roads_2016	roads, network, grenada	Road network of Grenada, checked by Mjueeb Alam and Cees van Westen (ITC) in 2015	Caribbean Handbook on Risk Information Management (CHARIM); the website also has a set of maps that use these layers http://charim-geonode.net/people/profile/grenada/?content=layers	No	Feature class - line	roads type (unpaved, main or roads), lenght	GCS: WGS 84 Datum: World Geodetic System 1984	n.g.	Vector; classified as main, secondary or tertiary roads		Jan 01 2014 - Dec 31 2015. Published to CHARIM: April 1, 2016	
Population per building	population_per_building_2014	residential, demographics, census, planning, Grenada	Estimation of population per residential building carried out by Mujeeb Alam, ITC, University of Twente, Netherlands	Caribbean Handbook on Risk Information Management (CHARIM); the website also has a set of maps that use these layers http://charim-geonode.net/people/profile/grenada/?content=layers	No	Feature class - polygon	Object ID, Shape Length (perimeter), Shape area, Use type, Occupancy, Parish, Enumeration district ID, Building population	GCS: WGS 84 Datum: World Geodetic System 1984	n.g.	Vector; shape area, use type, building pop	# people	Jan 01 2014 - Jan 01 2015	This is an estimation based on population data from the census bureau which was distributed over the residential buildings within the Enumeration district, based on the building size
Census enumeration districts	ed_2014	enumeration districts, census, central statistical office, planning	Census Enumeration Districts from the Central Statistical Office (CSO), Ministry of Finance, government of Grenada	Caribbean Handbook on Risk Information Management (CHARIM); the website also has a set of maps that use these layers http://charim-geonode.net/people/profile/grenada/?content=layers	No	Feature class - polygon	Enumeration district name/number, perish location, Enumeration district ID, area	GCS: WGS 84 Datum: World Geodetic System 1984	n.g.	Vector; shows census enumeration boundaries		Jan. 1, 2014 - Dec. 31, 2014	
Buildings (new)	buildings_2014_C	buildings, planning, Grenada	Building footprints of Grenada, edited and updated from old vector data by Mujeeb Alam and Cees van Westen (ITC, University of Twente, Netherlands) with attributes on occupancy types.	Caribbean Handbook on Risk Information Management (CHARIM); the website also has a set of maps that use these layers http://charim-geonode.net/people/profile/grenada/?content=layers	No	Feature class - polygon	Shape Length (perimeter), Use type, Occupancy, Enumeration district, Dwelling (y/n), Size	GCS: WGS 84 Datum: World Geodetic System 1984	n.g.	Vector; includes use type info	Metres	Jan 01 2014 - Jan 01 2015	
Soils	soil_inventory_2016	soils, grenada,	Soil map of Grenada, modified from original map of UWI (1959) by Cees van	Caribbean Handbook on Risk Information Management (CHARIM); the website also has a set of maps that use these layers http://charim-geonode.net/people/profile/grenada/?content=layers	No	Feature class-polygon	Description of soils, shape area, gridcode for soil type	GCS: WGS 84 Datum: World Geodetic System 1984	n.g.	Vector; polygon		Apr-16	

			Westen (ITC) through integration with slope map generated from LIDAR DEM and several other thematic maps										
Land use	Landuse_2015n11	land use, raster	Landuse map generated by Colm J Jordan and Stephen Grebby (British Geological Survey, Natural Environment research Council) from Pleiades images from 2011	Caribbean Handbook on Risk Information Management (CHARIM); the website also has a set of maps that use these layers http://charim-geonode.net/people/profile/grenada/?content=layers	No	Raster feature class	count, classifcation 1-15	GCS: WGS 84 Datum: D_WGS_1984	n.g.	Raster; 15 use types	GRAY_INDEX	Jan 01 2014 - Jan 10 2015	No index? Only a legend with a 1-15 classification. Raster data, almost on a graduating scale from CHARIM
DEM (Digital Elevation Model)	DEM_2016	DEM, Grenada, Digital Elevation Model	Digital Elevation model of Grenada was generated by Cees van Westen (ITC) from LIDAR data with holes filled up with SRTM (shuttle radar topography mission) data. Pixel size is 5 meters.	Caribbean Handbook on Risk Information Management (CHARIM); the website also has a set of maps that use these layers http://charim-geonode.net/people/profile/grenada/?content=layers	No	raster feature class	DEM	GCS: WGS 84 Datum: World Geodetic System 1984	5m	Raster; tif	GRAY_INDEX	not given; data was published March 2016	
Grenada Boundary	country_bound	boundary	Grenada country boundary	Caribbean Handbook on Risk Information Management (CHARIM); the website also has a set of maps that use these layers http://charim-geonode.net/people/profile/grenada/?content=layers	No	Feature class - polygon	shape area, name	GCS: WGS 84 Datum: D_WGS_1984	n.g.	Vector; polygon		April 1, 2016	
Household outer wall material, 2001	wall_material_2001	residential, construction, buildings, materials, Grenada	Households in dwelling units by type of outer wall material, 2001	Grenada National Census Report 2001	No	Table	Wall material, Total households, Rest of St Georges, Town of St Georges, St Johns, St Marks, St Patricks, St Andrews, St Davids, Carraicou		Parish	6 material categories	# households	2001	
Household outer wall material, 2011	wall_material_2011	residential, construction, buildings, materials, Grenada	Households in dwelling units by type of outer wall material, 2011	Grenada National Census Report 2011	No	Table	Wall material, Total households, Rest of St Georges, Town of St Georges, St Johns, St Marks, St Patricks, St Andrews, St Davids, Carraicou		Parish	9 material categories	# households	2011	
Household material of construction, 2001	material_construction_2001	residential, construction, buildings, materials, Grenada	Households by material of construction, 2001	Grenada National Census Report 2011	No	Table	Construction material, Total households, Rest of St Georges, Town of St Georges, St Johns, St		Parish	4 material categories	# households	2001	

							Marks, St Patricks, St Andrews, St Davids, Carraicou						
Household material of construction, 2011	material_construction_2011	residential, construction, buildings, materials, Grenada	Households by material of construction, 2011	Grenada National Census Report 2011	No	Table	Construction material, Total households, Rest of St Georges, Town of St Georges, St Johns, St Marks, St Patricks, St Andrews, St Davids, Carraicou		Parish	4 material categories	# households	2011	
Household year of construction, 2001	household_construction_year_2001	residential, construction, buildings, Grenada	Dwelling units by year built, 2001	Grenada National Census Report 2001	No	Table	Year, Total households, Rest of St Georges, Town of St Georges, St Johns, St Marks, St Patricks, St Andrews, St Davids, Carraicou		Parish	By decade	# households	2001	
Household year of construction, 2011	household_construction_year_2011	residential, construction, buildings, Grenada	Dwelling units by year built, 2011	Grenada National Census Report 2011	No	Table	Year, Total households, Rest of St Georges, Town of St Georges, St Johns, St Marks, St Patricks, St Andrews, St Davids, Carraicou		Parish	By decade to 2006, by year from 2007 to 2011	# households	2011	
Type of dwelling unit, 2001	dwelling_type_2001	residential, dwelling, buildings, Grenada	Type of dwelling by Parish, 2001	Grenada National Census Report 2001	No	Table	Type of dwelling, Total households, Rest of St Georges, Town of St Georges, St Johns, St Marks, St Patricks, St Andrews, St Davids, Carraicou		Parish	8 dwelling types	# households	2001	
Type of dwelling unit, 2011	dwelling_type_2011	residential, dwelling, buildings, Grenada	Type of dwelling by Parish, 2011	Grenada National Census Report 2011	No	Table	Type of dwelling, Total households, Rest of St Georges, Town of St Georges, St Johns, St Marks, St Patricks, St Andrews, St Davids, Carraicou		Parish	11 dwelling types	# households	2011	
Household roofing material	roof_material_2001	residential, construction, buildings, materials, Grenada	Number of households in dwelling units by material of roofing and Parish, 2001	Grenada National Census Report 2001	No	Table	Roof material, Total households, Rest of St Georges, Town of St Georges, St Johns, St		Parish	8 material categories	# households	2001	

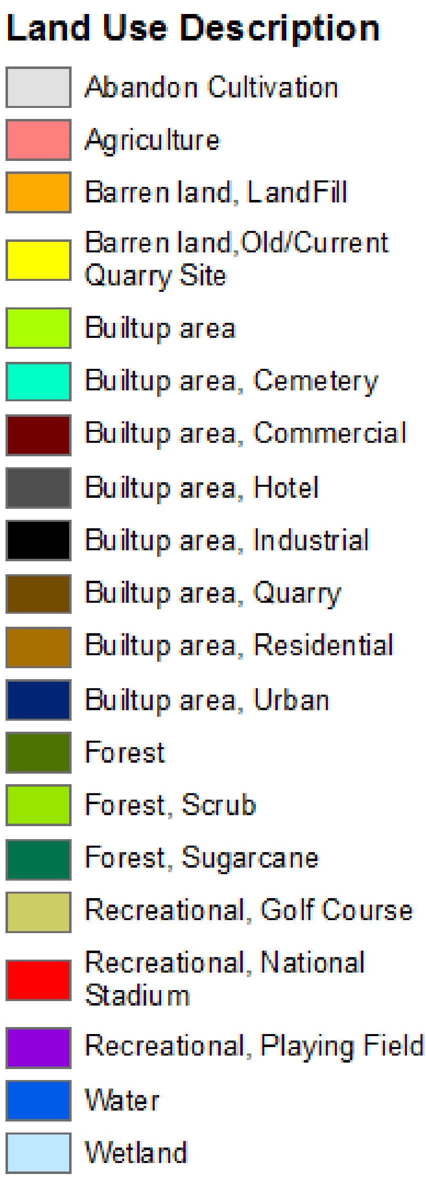
							Marks, St Patricks, St Andrews, St Davids, Carraicou						
Building applications	building_applications_2008_2017	buildings, planning, Grenada	Building application records from the Physical Planning Unit (PPU), Grenada. Details application date, proposed use and sq. footage for each application	Grenada Physical Planning Unit (PPU)	No	Table	Submission date, proposed use, site parish, site address, floor area		Town	Building use-type, floor area for most applications starting in 2009	Sq. metres	Jan 2008 - Sept 2017	
Electric distribution network	Awaiting shapefile from Grenlec			Grenada Electricity Services (GRENLEC)		Awaiting shapefile from Grenlec				Map of high voltage lines and devices in the network			
Land-cover map	Grenada/Land_Cover_data/	land use, land cover, environment, agriculture	Ministry of Agriculture land use/land cover data for Grenada for the years 1982, 2000 and 2009, and for Carriacou in 2001.	Ministry of Agriculture, Forestry & Fisheries, Government of Grenada	No	Feature class-polygon	Area, perimeter, land use ID, land cover code, hectares, acres, land use description, land cover description	GCS: WGS 84 Datum: D_WGS_1984		Vector		1982, 2000, 2001 (Carriacou, 2009	
Photos	Photos_Sept_2017, robphotos_Sept_2017, rob_photos_Sept_2017	buildings	Photographs, mostly of buildings, taken during Sept 2017 field work in Grenada. Relational database and associated index table.	Rob Symmes, 2017	No	Feature class - points (with file attachment)	Photo file path, File name, DateTime	GCS: WGS 84 Datum: World Geodetic System 1984		Photographs of buildings and other landmarks		Sept 17 - 29 2017	Have to have photofile to link to Geodatabase.
Buildings Open Street Network	buildings_2018_osm	buildings, open street map, commercial, residential, names	Building data found from Open Source map, contributed by thousands of individuals. Contains building footprints and various attributes. Open sourced data also found from some national mapping agencies.	Open Street Map : Volunteered Geographic Information © OpenStreetMap contributors https://www.openstreetmap.org/#map=12/12.1058/-61.6875	No	Feature Class-polygon	name, highway, waterway, aerialway, barrier, man_made, other tags, length	GCS: WGS 84 Datum: D_WGS_84		Feature class: buildings, residential, commercial, tourist, etc		Retrieved Jan 11, 2018	
Roads, Open Street Network	roads_water_ferry_osm_2018	Rivers, roads, ferryways, open street map	Vector line data found from Open Source map, contributed by thousands of individuals. Contains rivers, waterways, and any line data of Grenada coded through attribute data. Open sourced data also found from some national	Open Street Map : Volunteered Geographic Information © OpenStreetMap contributors https://www.openstreetmap.org/#map=12/12.1058/-61.6875	No	Feature Class - line	name, type, craft, amenity, admin_level, barrier, boundary, shop, office, man_made, tourism, other tags, length, area,	GCS: WGS 84 Datum: D_WGS_84		Feature class: rivers, roads, any line data from open street map		Retrieved Jan 11, 2018	

			mapping agencies.										
Damages to Gov't, Health, Education and Transportatio n Sectors, Hurricane Ivan	Ivan_sectors_damage	hurricane, Ivan, damage, sectors, buildings, Grenada	Damages to Gov't, Health, Education and Transportation Sectors from Hurricane Ivan. From a preliminary assessment report by the World Bank.	Grenada, Hurricane Ivan - Preliminary Assessment of Damages, September 17, 2004 - The World Bank	No	Table	facility type, sector, location, parish, damage assessment		Parish	Damage assessment uses the following scale: ND No damages Level 1 Windows, doors and furnishing destroyed or damaged Level 2 Partial roof covering destroyed or damaged Level 3 Roof structure destroyed or damaged Level 4 Complete roof destroyed Level 5 Significant damage to structural frame	See scale	Sept 17, 2004	
Housing Damages, Hurricane Ivan	Ivan_housing_damage	hurricane, Ivan, damage, residential, dwelling, buildings, Grenada	Percentage of housing by Parish with different levels of damage following Hurricane Ivan. From a preliminary assessment report by the World Bank.	Grenada, Hurricane Ivan - Preliminary Assessment of Damages, September 17, 2004 - The World Bank	No	Table	parish, percent ND, percent 1, percent 2, percent 3, percent 4, percent 5		Parish	Damage assessment uses the following scale: ND No damages Level 1 Windows, doors and furnishing destroyed or damaged Level 2 Partial roof covering destroyed or damaged Level 3 Roof structure destroyed or damaged Level 4 Complete roof destroyed Level 5 Significant damage to structural frame	%	Sept 17, 2004	
Damage by tourist accomodatio n, Hurricane Ivan	Ivan_hotels_damage	tourism, hurricane, Ivan, damage,hotel s, buildings, Grenada	Sample of room damage by tourist accommodation s.	Grenada: Macro-Socio-Economic Assessment of the damages caused by Hurricane Ivan September 7,2004, OECS	No	Table	Accomodatio n name, category, location, parish, capacity in units., # units destroyed, #		Town			2004	

							units damaged						
Tourist accomodatio ns functionally closed, Hurricane Ivan	Ivan_hotels_closed	tourism, hurricane, Ivan, damage,hotel s, buildings, Grenada	List of tourist accommodation s functionally closed due to Hurricane Ivan.	Grenada: Macro-Socio-Economic Assessment of the damages caused by Hurricane Ivan September 7,2004, OECS	No	Table	Accomodatio n name, town, parish, % of country's room cap., % of country's bed cap.		Town		%	2004	
Estimated affected population, Hurricane Ivan	Ivan_est_affected_pop	hurricane, Ivan, population, Grenada	Estimated Affected Population by Parish, from 2005 World Bank report "Grenada: A nation rebuilding"	2005 World Bank report: "Grenada: A nation rebuilding"	No	Table	Statistic, St Georges, St Andrews, St Johns, St Davids, St Marks, St Patricks, Carriacou, Total		Parish		#, %	2005	

B. Occupancy class samples

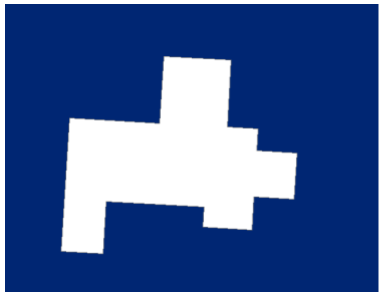
For the following examples of occupancy classes, the CHARIM building footprints have a coloured background. This represents the land use associated with the area the building is situated in. The legend on the right provides the land use descriptions corresponding to each colour code.



<u>100 - INSTITUTIONAL</u>

<u>CLASSIFICATION CODE: 110</u>
<u>Institutional: Church/Religious Place</u>

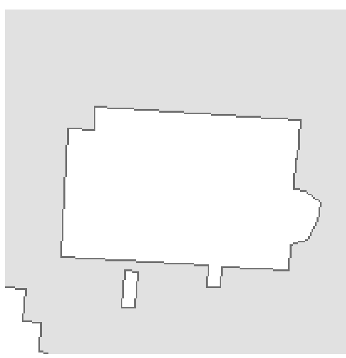
St. John's Anglican Church



(CHARIM Building Footprints) (Google Imagery, 2017)

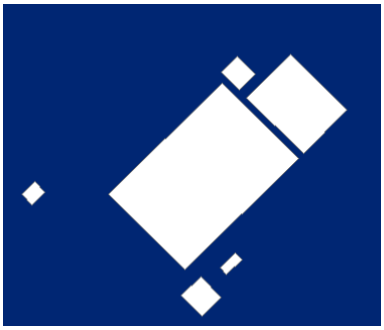
(Google Photos)

St. Matthew's Catholic Church



(Google photos) (CHARIM Building Footprints) (Google Imagery, 2014)

St. Patrick's Anglican Church



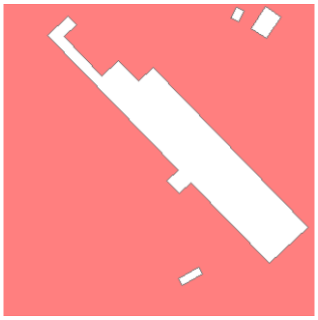
(Google photos) (CHARIM Building Footprints) (Google Imagery, 2015)

CLASSIFICATION CODE: 120
Institutional: School / Education centre

St. Patrick's Anglican School

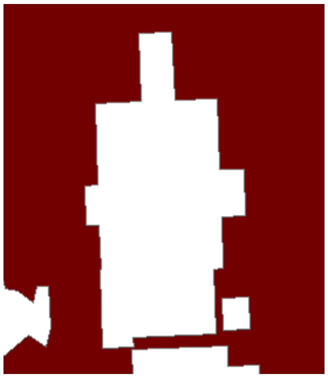
(CHARIM Building Footprints) (Google Imagery, 2015)

Belair Government School



(Google photos) (Google Imagery, 2014) (CHARIM Building Footprints)

WINDREF Research Institute- Part of St. George's University




(CHARIM Building Footprints) (Google Imagery, 2017)

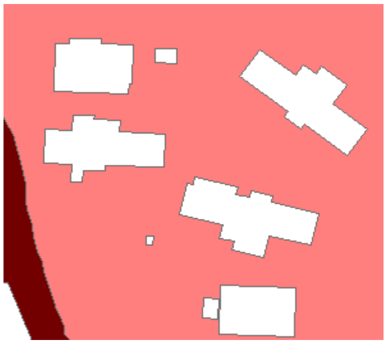
CLASSIFICATION CODE: 130
Institutional: Health / Hospital

131 - Major hospital
Grenada General Hospital



(CHARIM Building Footprints) (Google Imagery, 2017) (Google Photos)

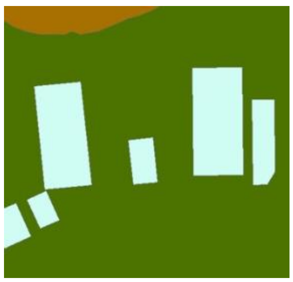
132 - Minor hospital/Health centre
Mt. Gay Hospital - established in 1986-1987



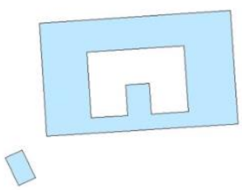
(CHARIM Building Footprints) (Google Imagery, 2017) (Ministry of Health-Grenada, 2016)

CLASSIFICATION CODE: 140
Institutional: Government office

Ministry of Education



(MoE Facebook page) (CHARIM Building Footprints) (Google Imagery)



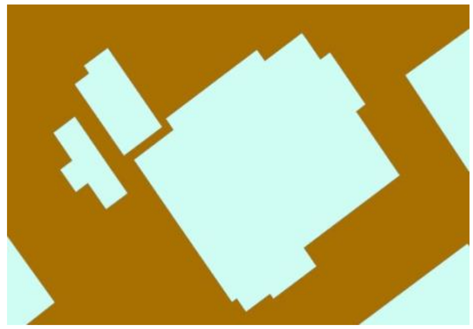
(OpenStreetMap)

<u>200 - INDUSTRIAL/COMMERCIAL</u>

<u>CLASSIFICATION CODE: 210</u>
<u>Industrial/Commercial: Commercial</u>

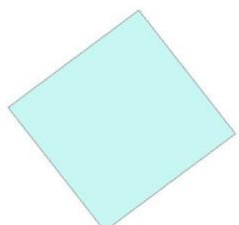
Bulk Buy Frozen Foods

(Field Work Photos)



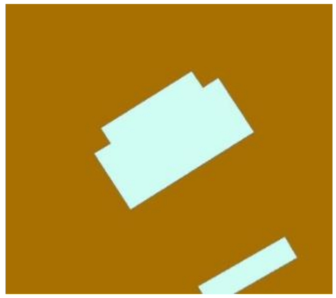
(CHARIM Building Footprints)

(Google Imagery)

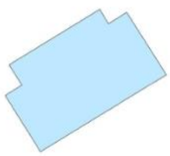


(OpenStreetMap)

Republic Bank in The Lime, St George

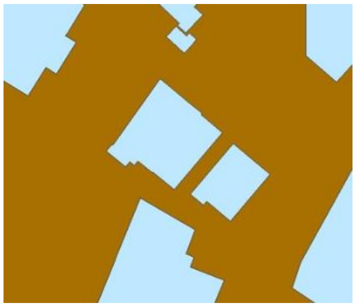


(Field work photos) (CHARIM Building Footprints) (Google Imagery)

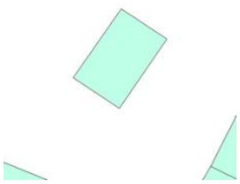


(OpenStreetMap)

<u>CLASSIFICATION CODE: 220</u>
<u>Industrial/Commercial: Urban-area mixed commercial</u>
Commercial building in Grenville, St Patrick



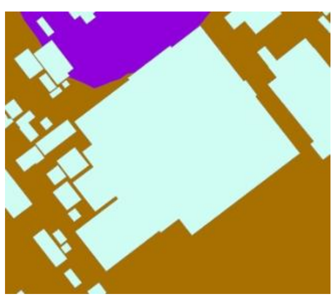
(Field work photos) (CHARIM Building Footprints) (Google Imagery)



(OpenStreetMap)

<u>CLASSIFICATION CODE: 230</u>
<u>Industrial/Commercial: Industrial</u>

231 - Grenada Breweries Ltd

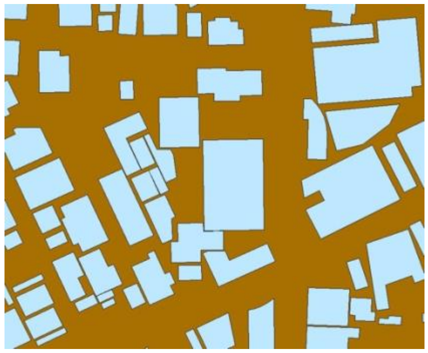


(Google Photos)

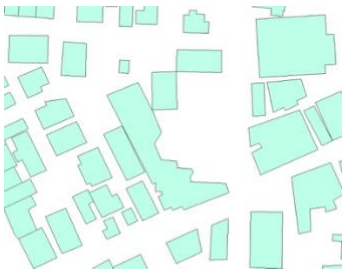
(CHARIM Building Footprints) (Google Imagery)

CLASSIFICATION CODE: 240
Industrial/Commercial: Commercial/Dwelling Mix

241 - Built-up area in Town of St George

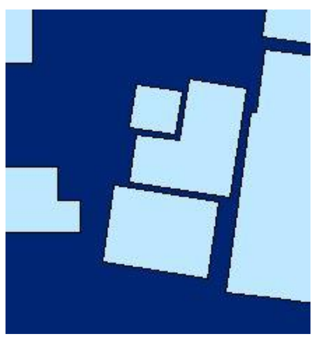


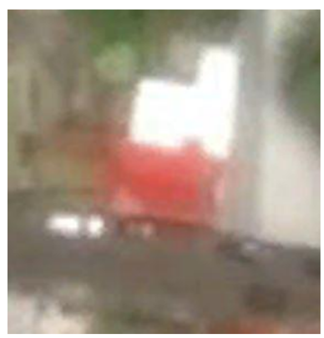
(Field work photos) (CHARIM Building Footprints) (Google Imagery)



(OpenStreetMap)

Business/residence in Sauteurs, St Patrick



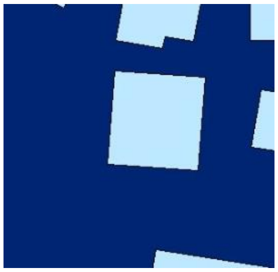


(Field work photos) (CHARIM Building Footprints) (Google Imagery)

300 - RESIDENTIAL

CLASSIFICATION CODE: 310
Residential: Urban single-family dwelling

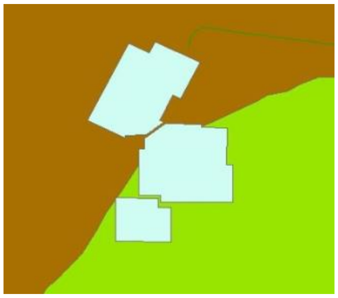
Residence in Sauteurs, St Patrick



(Field work photos) (CHARIM Building Footprints) (Google Imagery)

CLASSIFICATION CODE: 320
Residential: Residential area multi-family apartment

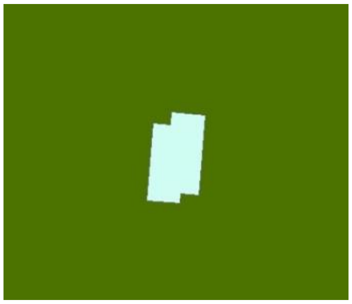
Premium Properties Apartments



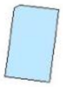
(Google Photos) (CHARIM Building Footprints) (Google Imagery)

<u>CLASSIFICATION CODE: 330</u>
<u>Residential: Rural single-family dwelling</u>

Dwelling in St David

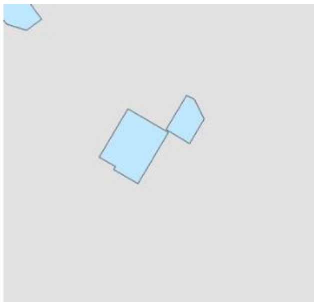


(Field work photo) (CHARIM Building Footprints) (Google Imagery)



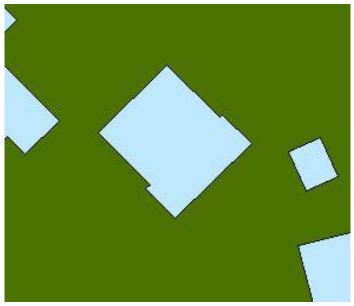
(OpenStreetMap)

Ex. 2: Dwelling in St Andrew

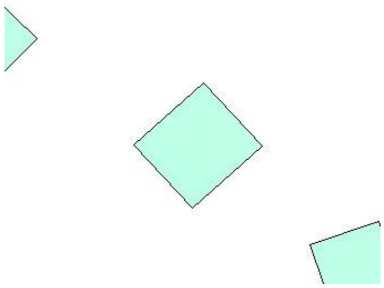


(Field work photos) (CHARIM Building Footprints) (Google Imagery)

CLASSIFICATION CODE: 340
Residential: Residential area single-family dwelling



(Field work photos) (CHARIM Building Footprints) (Google Imagery)



(OpenStreetMap)

400 - TOURISM

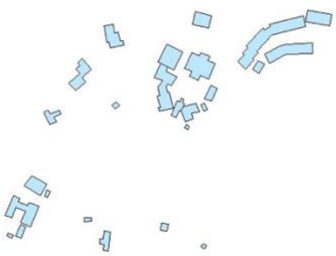
CLASSIFICATION CODE: 410
Tourism: Beach Resort

Sandals Grenada

(Field work photos)

(CHARIM Building Footprints)

(Google Imagery)

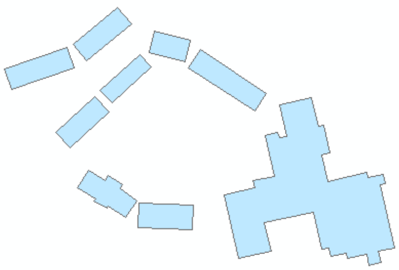


(Open Street Map)

Grenadian by Rex Resorts



(CHARIM Building Footprints) (Google Imagery, 2017) (Google Photos)



(OpenStreetMap)

<u>500 - CULTURAL</u>

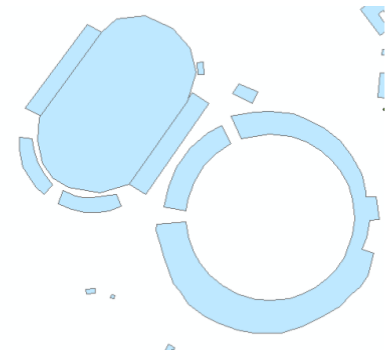
<u>CLASSIFICATION CODE: 510</u>
<u>Cultural: Stadium</u>

National Cricket Stadium and Kirana James Athletic Stadium



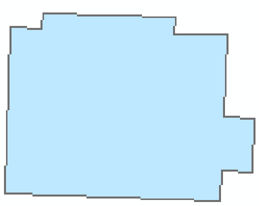
(Google Images, 2017)(CHARIM

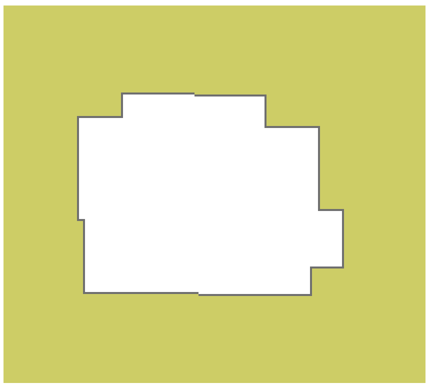
Building Footprints) (Google Photos)



(Open Street Map) (Field Work Photos) (Field Work Photos)

CLASSIFICATION CODE: 520
Cultural: Recreational
Golf Course- Grenada Golf Course



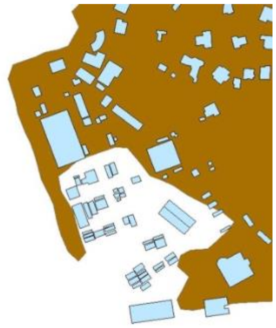


(Open Street Map) (CHARIM Building Footprints) (Google Imagery)

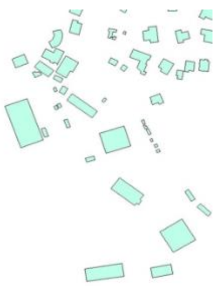
600 - TRANSPORTATION

CLASSIFICATION CODE: 610
Transportation: Seaport

Grenada Port Authority



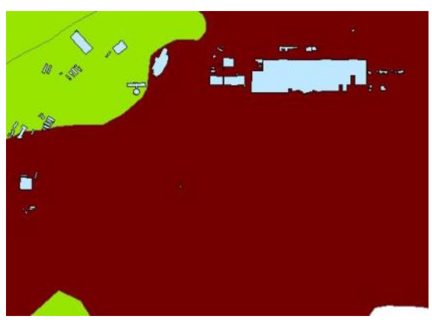
(Field work photos) (CHARIM Building Footprints)



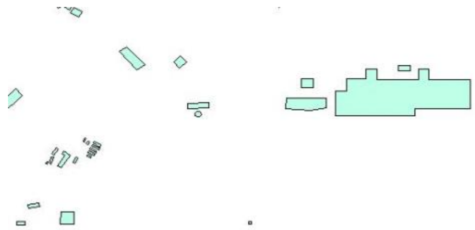
(Google Imagery) (OpenStreetMap)

CLASSIFICATION CODE: 620
Transportation: Airport

Maurice Bishop International Airport



(Google Photos) (CHARIM Building Footprints)



(Google Imagery) (OpenStreetMap)

C. Uncertainty & Sensitivity Analysis

Uncertainty in the Material Stock Analysis

The stock-driven (also known as bottom-up) approach used in the material stock analysis relies on the assumption that the buildings in each occupancy class (OC) are homogenous. Uncertainty is introduced in two ways due to this: Firstly, not every building in an OC is identical in terms of height and material intensities; and secondly, if there are potential inaccuracies in the building heights and material intensities themselves, uncertainty can be introduced to significant portions of the building stock. To examine this potential uncertainty, sensitivity analyses of assumptions regarding height and material intensity are shown below and discussed.

Sensitivity analysis: Building height assumptions

Sensitivity analysis was conducted for building height assumptions due to their importance for accurately estimating gross floor area (GFA) and thus calculating material stock results. Table C1 shows the effect changing an assumption for each occupancy class by ±1 floor has on final material stock amounts. For occupancy classes where a height of 1 floor was assumed, only a +1 floor change can be realistically considered.

Table C1: Sensitivity analysis of building height assumptions, by occupancy class. Percent (%) change in total MS calculation as a result of a change of ±1 floor is shown.

Code	Description	Original Height Assumption (# floors)	% change in total MS
111	Cathedral	3	0.1%
112	Church/chapel	2	0.2%
121	Educational campus building	3	0.9%
122	Standalone elementary/secondary school	2	0.7%
131	Major hospital	4	0.1%
132	Minor hospital/health center	1	0.1%
140	Government office	2	0.1%
210	Commercial	1	2.7%
220	Urban-area mixed commercial	2	1.7%
230	Industrial	1	3.2%
241	Urban-area commercial/dwelling mix	3	0.6%
242	Rural/residential-area commercial/dwelling mix	2	0.1%
310	Urban-area single-family dwelling	2	0.9%
321	High density-area apartment	3	0.1%

322	Low density-area apartment	2	4.5%
330	Rural-area single-family dwelling	1	31.5%
340	Residential-area single-family dwelling	2	12.3%
411	Large multi-unit hotel building	3	3.6%
412	Small hotel cottage/villa	1	2.6%
510	Stadium	4	0.2%
520	Recreational/community center	1	0.1%
530	Historic building	2	0.0%
610	Seaport	2	0.6%
620	Airport	2	0.3%
630	Bus terminal	1	0.0%

The largest classes by total footprint area make the largest contribution to material stock, and thus variation building height assumptions for these classes have the largest effect on the results. For example, a ±1 floor change for 330 – Rural-area single-family dwelling results in a 31.5% change in the material stock account. Thus, it can be seen that accuracy of the classification system developed in this thesis may have a significant impact on uncertainty in conjunction with the building height estimates; an inaccurate building height estimate assigned to an occupancy class with a large number of buildings will have a larger impact on accuracy of final material stock calculations than with a smaller class of buildings. A second consideration is the accuracy of footprint sizes from the CHARIM data, which is not known from this source. Due to the nature of this model of the building material stock, any error in the footprint sizes would be reflected proportionally in the material stock calculations.

Sensitivity analysis: Material intensity

Sensitivity analysis of material intensity (MI) values was conducted by analyzing the total GFA that each of the material intensity typologies represent, and calculating the change in total MS calculations were the MI for each material in each typology deviated by ±25%. As with building height assumptions, a physical constraint had to be considered: for typologies where the mean timber MI was 0, a deviation of +0.01 tonnes/m^2 is used as a negative MI is not possible. The results are shown in Table C2.

Table C2: Sensitivity analysis of material intensity (MI), by material intensity typologies for buildings. Percent (%) change in total MS calculation as a result of a change of ±25% deviation from original mean MI is shown.

			Mean MI (used for main Results)				% Change in total MS from +/-25% deviation from mean MI			
MI Typology	**GFA (sq.m)**	**% of Total GFA**	**Aggregate**	**Timber**	**Concrete**	**Steel**	**Aggregate**	**Timber**	**Concrete**	**Steel**
Concrete Structure 1	1414838	16.7%	0.045	0.04	1.315	0.027	0.1%	0.1%	3.9%	0.1%
Concrete Structure 2	3297009	38.9%	0.159	0.04	1.645	0.036	1.1%	0.3%	11.3%	0.2%
Timber Structure	1980773	23.4%	0.045	0.09	0.345	0.036	0.2%	0.4%	1.4%	0.1%
Concrete/Timber Mix Structure	848902	10.0%	0.159	0.09	1.125	0.035	0.3%	0.2%	2.0%	0.1%
Reinforced Concrete Structure	744612	8.8%	0.159	0	1.125	0.18	0.2%	0.1%	1.8%	0.3%
Brick Historical Structure	36163	0.4%	0.159	0.09	0.675	0.035	0.0%	0.0%	0.1%	0.0%
Steel Structure	39405	0.5%	0.159	0	1.645	0.325	0.0%	0.0%	0.1%	0.0%

The largest effect on the total MS calculations would come from variation in concrete intensity, and particularly for the Concrete Structure 2 typology, which accounts for about 40% of all gross floor area in buildings in Grenada. This is an important result in that it highlights the specifically reducing the uncertainty in concrete material intensity estimates, as this is a key structural material for buildings in Grenada.

In conclusion, there are three important areas of focus to minimize uncertainty in the material stock analysis: i) Ensuring the classification system has been refined sufficiently so that the homogeneity of each occupancy class is an appropriate representation of Grenada's buildings; ii) accurately estimating the building heights using a larger statistical sample, or with other remote sensing methods (see Discussion), and iii) further investigating and reducing the uncertainty of concrete material intensities for the construction typologies.

Uncertainty in the Future Scenarios

The main source of uncertainty in the analysis of the "Ivan-II" event was to accurately estimate the timber stock losses corresponding to the qualitative damage assessment scale used by the World Bank. To acknowledge this source of error, three varying levels of severity were presented in the Results section. It is also important to note that there has likely been some change in reinforcement of structures since Hurricane Ivan in 2004, so actual prevalence of damages may be different were the storm to hit the 2014 building stock.

Uncertainty in the results of the sea-level rise scenarios is dependent on the accuracy of the digital elevation model (DEM) used to estimate the elevation of buildings above sea-level. The horizontal resolution of the DEM was 5 meters, but accuracy of the elevation measurements for each pixel is unknown.

Uncertainty in the Material Flow Analysis

Sensitivity analysis: Sand and gravel estimates

Table C3 below presents the different values used in MFA literature for estimating inputs of sand and gravel relative to unit consumption of cement. The main results of this thesis use the value from Miatto et al. (2017), however this section shows the variation in DE (for concrete production only) estimates based on each of the values. The difference in DE is simply proportional to the difference in magnitude of values (see Figure C1). Since ratios of sand/gravel to cements were not known for Grenada, the coefficient from Miatto et al. (2017) was used to remain consistent with the Global Material Flows Database, but nonetheless this is a potential source of uncertainty. In terms of other Caribbean studies, the coefficient from Weisz et al. (2007) was used by Eisenhut (2009) in a material flow analysis for Cuba.

Table C3: Values in literature for calculating input [t] of sand and gravel per unit consumption [t] of cement.

Source	$\lambda_{concrete}$	**% difference from Miatto et al. (2017)**
Miatto et al. (2017)	**5.26**	--
Eurostat (2013)	6.09	+15.8%
Krausmann et al. (2009)	6.5	+23.6%
Weisz et al. (2007)	6.1	+16.0%

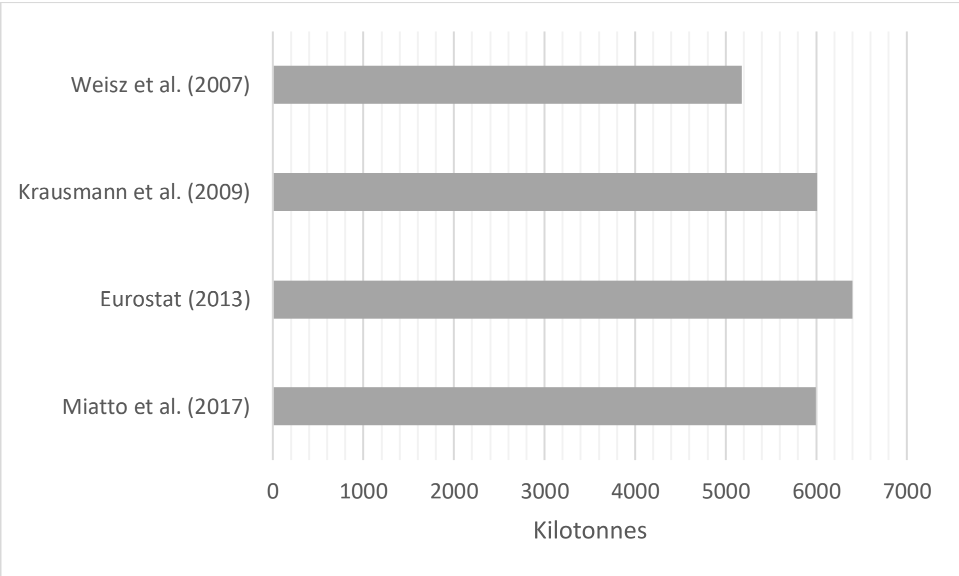


Figure C1: Absolute value of domestic extraction for production of concrete, calculated using the different cement-gravel/sand mix ratios from industrial ecology literature.

While the choice of coefficient obviously impacts domestic extraction (DE) calculations, the general takeaway from this section of results remains unchanged: DE of non-metallic minerals in Grenada dominates the construction material flow accounts from 1993 to 2009 in order to supply the production of concrete for use in the construction sector.

D. UN Comtrade Database Commodity Codes

Table D1: UN Comtrade database commodity codes and descriptions for wood.

Code	Commodity
4403	Wood in the rough, whether or not stripped of bark or sapwood, or roughly squared
4404	Hoopwood; split poles; piles, pickets, stakes of wood, pointed, not sawn lengthwise; wooden sticks, roughly trimmed, not turned, bent, etc., suitable for walking sticks, umbrellas, tool handles, etc.
4406	Railway or tramway sleepers (cross-ties) of wood
4407	Wood sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or end-jointed, of a thickness exceeding 6mm
4407	Wood sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or end-jointed, of a thickness exceeding 6mm
4408	Sheets for veneering (including those obtained by slicing laminated wood), for plywood or for similar laminated wood and other wood, sawn lengthwise, sliced or peeled, planed or not, sanded, spliced or end-jointed, of a thickness not exceeding 6 mm
4409	Wood (including strips, friezes for parquet flooring, not assembled), continuously shaped (tongued, grooved, v-jointed, beaded or the like) along any edges, ends or faces, whether or not planed, sanded or end-jointed
4410	Particle board, oriented strand board (OSB) and similar board (e.g. waferboard) of wood or other ligneous materials, whether or not agglomerated with resins or other organic binding substances
4411	Fibreboard of wood or other ligneous materials, whether or not bonded with resins or other organic substances
4412	Plywood, veneered panels and similar laminated wood
4413	Densified wood, in blocks, plates, strips or profile shapes
4418	Builders' joinery and carpentry of wood, including cellular wood panels, assembled flooring panels, shingles and shakes

Table D2: UN Comtrade database commodity codes and descriptions for iron and other metals.

Code	Commodity
2601	Iron ores and concentrates; including roasted iron pyrites
2603	Copper ores and concentrates
2604	Nickel ores and concentrates
2606	Aluminium ores and concentrates
2607	Lead ores and concentrates
2608	Zinc ores and concentrates
2609	Tin ores and concentrates
72	Iron and steel
73	Iron or steel articles

74	Copper and articles thereof
75	Nickel and articles thereof
76	Aluminium and articles thereof
78	Lead and articles thereof
79	Zinc and articles thereof
80	Tin; articles thereof

Table D3: UN Comtrade database commodity codes and descriptions for nonmetallic minerals.

Code	Commodity
2505	Natural sand except sand for mineral extraction
2506	Quartz (except natural sands) and quartzite
2507	Kaolin and other kaolinic clays
2508	Clay nes (except expanded clay for insulation)
2514	Slate
2515	Marble, travertine, ecaussine etc
2516	Granite, porphyry, basalt, sandstone, etc.
2517	Pebbles, gravels, aggregates and macadam
2518	Dolomite
2519	Natural magnesium carbonate, magnesium oxide
2520	Gypsum, anhydride, gypsum plaster
2521	Limestone materials for manufacture of lime or cement
2522	Quicklime,slaked, hydraulic lime for construction etc.
2523	Cement (portland, aluminous, slag or hydraulic)
2526	Natural steatite
2714	Bitumen and asphalt, natural; bituminous or oil shale and tar sands; asphaltites and asphaltic rocks
6801	Stone; setts, curbstones and flagstones, of natural stone (except slate)
6802	Monumental or building stone, worked (except slate) and articles thereof (not of heading no. 6801) mosaic cubes etc., of natural stone including slate; artificially coloured granules of natural stone
6803	Slate, worked; and articles of slate or of agglomerated slate
6807	Asphalt or similar material; articles (e.g. petroleum bitumen or coal tar pitch)

6808	Panels, boards, tiles, blocks and the like; of vegetable fibre, of straw, shavings, chips, particles, sawdust or other waste, of wood, agglomerated with cement, plaster or other mineral binders
6809	Plaster or compositions based on plaster; articles thereof
6810	Cement, concrete or artificial stone; whether or not reinforced, articles thereof
6811	Asbestos-cement, of cellulose fibre-cement or the like