Ecosystem services assessments on university campuses: A review

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Executive summary

The field of ecosystem services (ES) has been gaining academic attention since the Millennium Assessment Report in 2005, which highlighted the dramatic decline in biodiversity and ES to a global audience. Since then, there have been increasing efforts to mainstream ES considerations into policy making with a goal to design better policies for people and the environment. Universities are at the frontlines to push the ES agenda due to their unique position in society. As Nanyang Technological University (NTU) pursues its sustainability goals, this paper aims to assess the state of the art of integrated ES assessment for university campuses and propose recommendations for NTU to engage in such an exercise. The study reviews ES assessments done on campuses globally to understand the most common methods and how they have impacted on campus development plans. This review found suitable 30 studies in an initial filtering exercise and, after a thorough review, 28 of these studies were chosen to be analysed in detail. Using these results, the paper proposes steps towards an ES assessment for the campus to adopt. The step-by-step framework can serve as a foundation for a robust campus ES assessment to be developed for NTU in the near future, with the goal to mainstream ES considerations into campus management and policy.

Introduction

Ecosystem services (ES) assessments have been growing rapidly in importance in land use planning as highlighted by the Millennium Assessments which defines ES as "the benefits that people obtain from ecosystems" (McMichael et al., 2005). These may greatly impact the well-being of humans and thus needs to be carefully assessed when undertaking land use planning. Furthermore, the flow of ES has become more strained with a rapidly growing population plus the dwindling supply of ecosystems in the current context of global urbanisation (Wei et al., 2017). As such, ES assessments must be further integrated into land use planning to maximise human well-being and sustainable development. For that, universities may prove to be key actors towards this objective. University campuses have often been described as mini-cities and thus have often been used as a testbed for policies and initiatives before being scaled up to the city-level (X. Wang et al., 2021). This setting, coupled with the wealth of ideas provided by its student and academic population, allows them to be potential sites of ES assessment framework innovation. Also, as argued by Colding and Barthel (2017), universities possess a special influence on society. They educate and train people in or entering the workforce and participate in governance at the regional and national level (Colding & Barthel, 2017). This means that universities are well-positioned to advocate the practice of ES assessments as well.

Given the importance of integrating ES assessments in land-use planning and the special influence of universities on societies, there is a strong value in encouraging universities to adopt ES management practices into their campus development For that, we aim to conduct a review on the ES assessments conducted on campus so as to form a state-of-the-art ES assessment framework for universities to adopt, particularly for the Nanyang Technological University (NTU) in support of its sustainability objectives and to maximise nature's benefits on its internal and surrounding community. Hence, this paper will review the current literature of ecosystem service assessments done on campuses to set the foundation of this framework. We start this review with two main research questions:

- What are the most common methods for ecosystem service assessments on campus areas?
- How have these ecosystem service assessments been used to advise campus development policies?

In the following sections, the paper will first elaborate key terms to aid the understanding of ES assessments. Afterwards, the search methodology used in obtaining relevant studies and how they are classified. From there, this paper will describe the results of the search and go through the content found in the relevant papers. Finally, the findings would be summarised, and recommendations would be derived in the development of a robust ES evaluation framework for NTU.

Background

Types of Ecosystem Services

When we consider ecosystem services, there are a variety of such benefits to human well-being that are classified under four broad categories: Provisioning ES (which are resources provided by the ecosystem that are essential to human survival), Regulating ES (which are benefits to human wellbeing obtained through natural processes that maintain the health and quality of the surrounding environment), and Cultural ES (which are non-material benefits that humans may obtain from the ecosystem), and Supporting ES (services that help maintain the functions of other ecosystem services) (Rose, 2020). Ideally, a comprehensive integrated ES assessment of the area would include the measurement of many different ES among the four categories to not only understand the range of benefits that can be derived from the area but also identify potential conflicts and synergies between ES (McMichael et al., 2005). However, actual ES assessments may choose to exclude certain ES due to the difficulty of identifying and analysing its indicators or the lack of demand for the ES, such as how in urbanised settings, demand for provisioning ES is much lower as compared to rural areas (McMichael et al., 2005).

Sources and Indicators of Ecosystem Services

When conducting an ES assessment of an area, the types of natural capital to be measured must first be identified. Natural capital refers to the renewable and non-renewable natural resources that can contribute to the provision of ES to people. Natural capital may either be naturally occurring in the ecosystem or by design as green infrastructure which are the natural or semi-natural systems and features that are constructed or designed by people. These differs from grey infrastructure which are purely man-made structures and thus would not be considered as sources of ecosystem services. Identifying all the natural capital available would allow us to understand what ES are potentially available and the types of methodologies needed in assessing them. Measurements based on this in addition to other structural social and structural properties typically indicates the supply of ES available in the region. Knowing the amount of ES supply helps us understand the total potential of ES available in the area. However, as the concept of ecosystem services is centred on the benefits ecosystems can bring to humans, it is important to also assess the amount of ES realised in conjunction with measuring the supply of ES which can be done through also identifying ES demand indicators. ES demand indicators would either directly or indirectly highlight the amount of ES consumed in the area (Burkhard, Kandziora, Hou, & Müller, 2014). Hence, to have a comprehensive ES assessment, both ES supply and demand indicators must be analysed to understand how much of such ecosystem services are realised in the area.

Methodology

Campus ES Assessments

Given that our objective is to develop a state-of-the-art ES assessment framework for NTU to adopt, this paper would review ES assessment exercises conducted on campuses. This paper will define 'campuses' for this review as a land occupied by a university where its institutional buildings, facilities, and features are found. These buildings and features may be academic, residential, or non-academic in nature if it is under the university's administration. In finding past ES assessments conducted on campuses, this paper aims to derive methodologies and frameworks that can be replicable in the context of the NTU campus and thus, contribute to the formation of an integrated ES assessment framework.

Search Criteria

In search of past ES studies done on campuses, we first used the web engines Google and Google Scholar using the following search terms:

- **"assessing ecosystem services" & "campus"**
- **"ecosystem services assessment" & "campus"**
- **"ecosystem services" & "campus"**
- **"ecosystem services" & "planning" & "campus"**

To determine if the paper is relevant, the abstracts would be reviewed to check if there are any ES assessments conducted in campuses before adding them to the literature list to be reviewed. In the case of using google, theses and academic papers published by universities, peer-reviewed journal articles, and grey literature such as university or government documents would have their search entries reviewed to determine its initial relevance to the topic of research. Beyond these two search engines, we also searched through two science databases: Scopus and Web of Science, using the third and fourth search terms as shown and the same methodology in determining the relevance of the papers. The first and second search terms were not used as it would produce overlapping results with the broader third and fourth search terms in these two databases. Following this filtering process, the literature list would then be reviewed and assessed under three categories to understand its contribution to our research questions. These three categories, in order of priority, are: "Relevance", "Integrated", and "Detailed". Ranking of these three categories is shown in the table below.

"Relevance" would be determined based on whether the study is a clear ES assessment that leads to recommendations for future campus development. Those that do not outline how their findings contribute to campus planning but have conducted a pertinent ES assessment nonetheless would be deemed as "Methodologically Relevant". This category holds the highest priority as it indicates which articles are most likely to contribute to the formation of a campus ES assessment framework and thus would require deeper analysis. "Integrated" examines whether the study assessed multiple ES provided in the campus area. Ideally, a campus ES framework would account for the variety of ES benefits that is found in the campus. However, for studies that examines a specific ES, the methodology and approach would still be analysed to gain a greater wealth of knowledge on ES assessment frameworks. This criterion is important as since the overall objective is to construct an integrated ES assessment framework, integrated ES studies would shed light into how findings of different ES could be structured and interpreted together which could then be applied to the framework. "Detailed" would refer to how clear and in depth was the ES assessment explained in the study so that it may be easily adopted and replicated. Although the other two categories are of higher importance in analyses, this category would indicate how replicable the methodologies are and thus, informs on the usefulness of the relevant or methodologically relevant sources in furnishing details on the ES assessment framework.

Categories	**Option 1**	**Option 2**	**Option 3**
Relevance	Highly Relevant – ES assessment leading to recommendations for campus development	Methodologically Relevant – ES assessment method relevant but limited/lack of recommendations for campus development	Not Relevant – ES assessment found to not be the focus of the paper/ testing ES assessment methodology that may not be reliable yet.
Integrated	Integrated – Assessed two or more ES in the campus area	Single-ES – Only Assessed 1 ES in campus area	-
Detailed	3 – Detailed steps on conducting ES assessment such that it is easily replicable	2 – General flow of ES assessment outlined by insufficient details to be replicated	1 – No details specified on how ES assessment is conducted.

Table 1: Categories to classify literature.

Using this classification, the literature will be divided into three main groups based on the categories shown in Table 2, with group 1 having the highest priority of analysis. The first two groups are examined in depth because of their strong relevance to the contribution of a campus ES evaluation framework. A more generalised review would be done for the third group to support and complement the information found in the first two groups of literature.

	"Highly Relevant"	**"Methodologically Relevant"**
"Integrated"	**Group 1**	**Group 3**
"Not Integrated"	**Group 2**	

Table 2: Grouping of Literature Based on Classification of Content

As elaborated earlier, it is important to understand the amount of supply and demand present for an ecosystem service in the assessment. For that matter, it is important to also understand which of these aspects of ES reviewed in the selected literature to properly design a comprehensive ES framework. Using the conceptual framework provided by Burkhard et al. (2014) on understanding ES and their comprehensive list of indicators provided, the studies that were considered "relevant" or "methodologically relevant" will also be classified based on the type of analysis conducted for the ES assessment. These analyses may be on the 'ES supply' that indicates maximum potential yield of a service or the outputs of ES, or the 'ES demand' that measures how much ES are consumed (Burkhard et al., 2014). A list of ecosystem services and their possible supply and demand indicators as compiled by Burkhard et al. can be found in the appendix.

Summary of Review

Pool of papers

Upon initial search, it can be observed **that there have been few ES assessments conducted on campuses**. In total, 30 studies were chosen through the filtering process for further analysis. This lack of campus ES assessments may be due to the disconnect between the ES academia and campus planners themselves as identified by Rose (2020) where campus planners may acknowledge the importance of ES but do not really implement any measures in properly assessing them for campus planning considerations.

Notably, **most of the research, 25 papers, included analysis on the ES related to urban vegetation such as carbon sequestration or aesthetic effects**. In fact, 14 of them focus solely on urban vegetation. This is due to how plants are immobile and thus easily quantifiable through multiple methods ranging from on-site fieldwork to remote sensing techniques. **As for the categories of ES analysed, most papers focus on either regulating or cultural ES** other than one that calculated the potential value of provisioning ES together with other ES through the benefit transfer method as done by McCoy (2009). This lack of focus on provisioning ES is most likely due to how campus areas are mainly occupied by the student, faculty staff, and academic population rather who would not be constantly growing and extracting natural resources from the ecosystem unlike subsistence or agricultural farmers. Hence, there is little to no demand for the campus' provisioning ES and thus, are typically ignored by campus ES assessments. Although the campus demographic may not be actively demanding for certain regulatory ES such as macroclimate regulation, many of these studies still included their indicators into the assessment such as carbon sequestration. This is due to the nature of such regulating ES like how carbon sequestration of the campus trees contributes to climate regulation on a larger geographic scale and thus would have a strong demand from society. Thus, campus ES assessments

Through an in-depth review of all 30 studies, they were further classified based on the categories shown above. Three of them ended up being deemed "Not Relevant", while 15 were considered "Methodologically Relevant", and the remaining 12 were "Highly Relevant". Among the studies categorised as "Highly Relevant" or "Methodologically Relevant", it is found that 11 of them featured integrated ES assessments while 16 of them focuses on a single ES. Meanwhile, most of the studies feature clear details on the methodology and framework used for the assessment with 25 out of the 30 were found to have ranked 3 in the "detailed" category. This shows that the ES assessments done would have adequate information provided to be replicated when forming a comprehensive ES assessment framework. For the studies that are not considered as "detailed" (i.e., being categorised as 1 or 2), they can complement the rank 3 studies by offering insights on how the overall integrated ES framework may look like in which this would be further elaborated in the next section.

In the 27 studies that were considered "relevant" or "methodologically relevant", 10 has conducted their ES assessment through measuring both supply and demand indicators while 12 have done their studies solely on ES supply and 5 have done their studies solely on ES demand indicators. From the literature, the ES assessment tends to focus on supply indicators like measuring biomass for carbon sequestration potential or LU/LC type for water infiltration when studying regulating ES. For cultural ES, studies would tend to examine demand indicators instead such as obtaining public perception through surveying. The choice of pivoting the study to either supply or demand indicators in assessing a specific ES is likely to be heavily influenced by the ease of collecting data. The tangible nature of regulatory ES providers meant that it is relatively easier to identify the potential capacity of the ES in the area and hence supply indicators are opted for analysis. Meanwhile, the intangible nature of cultural ES meant that it is difficult to determine its manifestations and sources. Thus, qualitative data on users of ES is much easier to obtain. Certain studies only represented both the supply and demand of ES in their analysis through conducting an economic valuation of the ES potential. However, studies like Julian, Daly, and Weaver (2018)integrated ES assessment on blue spaces and Y. Wang, de Groot, Bakker, Wörtche, and Leemans (2017) assessment on thermal comfort has shown the possibility and importance of integrating more demand indicators for regulatory ES assessments through surveying the social background and experiences of users which may impact how they use or perceive ES. This would be explored more in the subsequent sections.

Summary of Group 1:

There were 6 studies that fit into the criteria of the first group where an integrated ES assessment is done to advise campus planning. However, half of them were classified under "Detailed" as rank 3, meaning that although these studies may be suitable case studies in forming an ES assessment framework, half of them lack details on how the ES assessment is carried out, making it difficult to fully replicate the assessment process that led to their recommendations.

Reviewing the ES assessed by the papers in group 1, most of them measured regulating ES such as climate regulation and water flow regulation and cultural ES such as landscape aesthetics. One study by McCoy (2009) has evaluated a variety of ES from all three categories however it was done through a conceptual assessment using Land use/Land Cover (LU/LC) data rather than onsite fieldwork. This further illustrates the focus on regulating and cultural ES for campus ES assessments over provisioning ES as explained in the earlier sections.

All the papers, except Coskun Hepcan & Hepcan's (2018) study, have accounted for both ES supply and demand indicators for their assessment. The less detailed studies, although lacking the exact methods needed to record such indicators, have clearly shown how the ES assessment can be broken down to assess and integrate the ES supply and demand factors. The assessments done in the Yale Campuses (Banerjee, Carlisle, Kaufman, & Schindall, 2011; Bouffard, Miley, Piana, & Strobo, 2011), for example, show how the careful identification and measures of biophysical indicators coupled with stakeholder assessments has allowed them to map out clear opportunities and obstacles for recommending ES improvements. The study by Calabria, Vick, and Cassity (2011) offers additional insights on the indicators to be recorded such as studying policy regulations within the campus to understand further potential challenges to ES development and identifying ecological patches and corridors within the campus to better maximise efforts on improving the ES in the campus. Meanwhile, some studies like Cantu's and McCoy only used economic indicators and not stakeholder surveys to account for the ES demand and thus the overall assessment of realised ES in the campus. Thus, they would have not accounted for the perception of the campus stakeholders on its ES which may differ from general economic indicators.

Looking at the methodologies specifically, we can observe a general structure of integrated ES assessments from the less 'detailed' studies by Calabria et al. and Yale Campuses assessment. The structure involves an analysis of the social patterns found in the campus, determining, and measuring the ES found in the area, and conducting stakeholder surveys plus policy reviews. This framework would allow the assessors to identify opportunities of improvement for ES in the campus and identify possible challenges that may occur either from stakeholders or policies. This would allow them to craft recommendations that would maximise the ES found in the campus that complements with the demands and preferences of stakeholders. Interestingly, Calabria et al.'s study has also shown how the campus ES assessments can be exported to graduate students through a module which may serve as a reference for the main assessment.

For the more ‘detailed’ studies, they have outlined specific techniques and practices to measure certain ES. For example, iTree Eco may be used to evaluate the multitude of ES associated with trees using a tree inventory data or water flow regulation can be assessed through using the runoff curve number method to determine rainwater runoff in the area (Cantu, 2015; Coskun Hepcan & Hepcan, 2018). However, the issue of using iTree Eco would be that the tree data it uses are based off the tree species United States and supported countries. As Singapore is not one of the supported countries, the iTree progamme may be incompatible for NTU. Also, one study has shown the **usefulness of LU/LC analysis in working out a quick rough valuation of ES in the campus using the benefit transfer method.** This method involves assigning a general biome to the LU/LC classification and then calculating the expected value of ES based on the global average value of ES for that biome. Furthermore, McCoy has used this method to illustrate the changes between the valuation of past ES and present in order to justify recommendations to improve on ES which has their value reduced over time. Hence, this may be a possible method to be adopted in comparing the historical changes of ES of a campus in order to craft recommendations.

Title	ES Assessed	ES Provider	Purpose	Dmnd?	Sply?	Study Area	Key Points
An Ecosystem Services Plan for Yale's Central Campus (Bouffard et al., 2011)	Water flow Regulation, Water purification, Local climate Regulation, Landscape Aesthetics	Urban Vegetation, Green Infrastructure	To identify problems in ES provision in the Central Campus - Demand & Supply Mismatch	Y	Y	Yale Central Campus	• Assessment framework split into three phases: Examine social patterns, assess ecosystem services potential and issues, stakeholder surveys • Recommendations on campus development based on understanding challenges and opportunities from observations
Assessing Regulating Ecosystem Services Provided by the Ege University Rectorship Garden (Coskun Hepcan & Hepcan, 2018)	Water flow regulation, Global Climate Regulation	Urban Vegetation, Green Spaces	Calculate three regulating services generated by Ege University Rectorship Garden	N	Y	Ege University Rectorship Garden	• Carbon storage and sequestration measured for assessing global climate regulation • Did not use specific biomass equations to calculate carbon storage, mainly general equations • Use of SCS-CN method to determine volume of runoff and thus, water flow regulation
Analysis of Ecosystem Services at Mullins Creek on the University of Arkansas Campus (McCoy, 2009)	Integrated*	Multiple Sources	Investigate the evolution in value of ES in Mullins Creek Watershed	Y	Y	Mullins Creek Watershed on University of Arkansas Campus	• Benefit transfer method to perform conceptual ES valuation on watershed area in campus • Past LU/LC data determined through historical records • Comparison of data to justify
Ecosystem Service Plan: Yale University School of Medicine	Water purification, Landscape Aesthetics	Urban Vegetation and Green Infrastructure	Assessing current state of ES	Y	Y	Yale Medicine Campus	• Similar structure to Yale Central Campus Assessment

Campus (Banerjee et al., 2011)							• Used case studies of similar medical campuses to justify ES improvements
UGA's Green Infrastructure Plan: Student Envisioned Plans to Improve Ecosystem Services on Campus (Calabria et al., 2011)	Integrated*	Multiple Sources	Conducting integrated ES assessment in the campus area for future campus plan	Y	Y	University of Georgia Campus	• Learning activity for graduate students to assess ES of campus and construct ES development plan for future • Process in 3 stages: Studying policy regulations, conducting stakeholder interviews, conducting ES inventory review • Identified hubs and linkages of ES for recommendations
Ecosystem Services of Urban Trees and The Impacts of Urbanisation (Cantu, 2015)	Global Climate regulation, Water flow regulation, Air Quality Regulation	Urban Vegetation	Value the regulating ecosystem services provided by urban trees	Y	Y	University of Texas - Rio Grande Valley Edinburg Campus	• Tree inventory check to collect data • Use of iTree Eco to assess various ES of Campus Trees. • Valuation of trees to inform potential cost incurred from loss of trees in an event of a disaster. University can use that information for insurance claims

*Various ES assessed but either too numerous for this table or not exactly specified

Table 3: Overview of ES Assessments Under Group 1

Summary of Group 2:

There were five studies that fall under the second group where they are considered "Relevant" but not "integrated" ES assessments. All of them have found to be very "detailed" with them classified under rank 3 and thus it would be easy to acquire information on replicating the methodologies used in these studies.

For the ecosystem systems assessed in this group, three out of five assessed the regulating ES of vegetation or green infrastructure, while the rest focused their studies on cultural ES. Thus, like group 1, regulating and cultural ES were the focus of campus ES assessments.

However, as opposed to group 1, there is only one study, that has accounted for both ES supply and demand indicators (Tonietto et al., 2021). Furthermore, that study mainly used economic indicators, rather than qualitative data, to represent ES demand. For the rest, half of them focused their assessment on demand indicators while the other assessed through ES supply indicators. **Strikingly, the two studies that assessed ES demand indicators were measuring cultural ES which are usually intangible in nature while the other two that assessed ES supply were assessing regulatory ES which are more quantifiable.** Hence, a possible factor in influencing the study to focus on demand or supply may be due to the ease of collecting the data for that category of ES.

In this group, more methodologies were offered for measuring global climate ES through carbon sequestration such as Cox (2012) use of the CUFR Tree Carbon Calculator (CTCC) which has the benefit of measuring carbon sequestration of individual trees. However, like iTree, this method uses data from certain regions in US and thus, may not be compatible in the context of NTU. Meanwhile, ENVI-met simulations have been used to simulate the impacts of campus trees on campus ambient temperatures, thus illustrating a probable method to measure the local climate regulation ES of vegetation (Wong & Jusuf, 2008). Although this method may not be accurate assessment of ambient temperatures in campus as compared to onsite measurements, it may potentially be a good way to visualise the rough impact of campus temperatures on the local climate. Also, Mt Akhir, Md Sakip, Abbas, and Othman (2020) has illustrated an easily replicable method of assessing the demand for landscape aesthetic ES of trees and shrubs (TAS). This involves showing interviewees several photographs of green spaces containing flowering TAS and duplicates where some of these TAS were edited out. The interviewees then rank the pictures based on landscape parameters and the authors could use this to observe the effect of TAS on these green spaces.

There were also notable observations from these group of studies that may provide further insights on certain assessment methodologies. Tonietto et al.'s method of supervised classification of LU/LC on satellite imagery may be a more reliable alternative to McCoy's interpretive method of classification and thus could be used on a proposed preliminary assessment of ES in the NTU campus**.** **Also, findings from Addas and Maghrabi (2021) on cultural ES have shown how the socio-demographic attributes of stakeholders in the campus may affect their perception and valuation of ES.** This suggests the need to account for socio-demographic backgrounds when conducting qualitative ES surveys.

Title	ES Assessed	ES Provider	Purpose	Dmnd?	Sply?	Study Area	Key Points
A Sustainability Initiative to Quantify Carbon Sequestration by Campus Trees (Cox, 2012)	Global Climate Regulation	Urban Vegetation	To take a tree inventory compilation of the California State University, Northridge and calculate carbon sequestration potential	N	Y	California State University, Northridge South Campus	• Use of CTCC to calculate carbon sequestration benefit for trees in database • Useful for assessing sequestration of individual trees • Spatial map of campus trees given compiled from this project given to campus management for their own use
GIS-based Greenery Evaluation on Campus (Wong & Jusuf, 2008)	Local Climate Regulation	Urban Vegetation, Green Infrastructure	Identify differences between temperatures of campus currently and after master plan due to urban heat island effect	N	Y	National University of Singapore Kent Ridge Campus	• Used ENVI-met simulations to project ambient temperatures of current scenario and campus plan based on greenery rate • Results of greater ambient temperatures in campus plan • Recommendations for more grass patches near buildings or installing green roofs on newly constructed buildings
Visual Quality Assessment of Trees and Shrubs in South Campus of Adnan Menderes University in Spring (Polat, Kiliçaslan, Kara, & Deniz, 2015)	Landscape Aesthetics	Urban Vegetation	Evaluating aesthetical value of colourful trees and shrubs and flowers	Y	N	Adnan Menderes University South Campus	• Interviewees ranked photographs of areas with and without colourful trees and shrubs • Ranking based on landscape parameters such as visual preferences and vividness

Social Evaluation of Public Open Space Services and Their Impact on Well-Being: A Micro-scale Assessment from a Coastal University (Addas & Maghrabi, 2021)	Cultural ES	Public Open Spaces	Examines Socio-cultural influence of Public Open Space Services	Y	N	King Abdulaziz University Campus	• Qualitative survey on impact of public opens spaces through questionnaires • Respondents indicated awareness and perception of cultural services • Socio-demographic attributes of stakeholders found to have impacted their responses
Towards a Carbon Neutral Campus: a Scalable Approach to Estimate Carbon Storage and Biosequestration, an Example from University of Michigan (Tonietto et al., 2021)	Global Climate Regulation	Urban Trees, Soil organisms	Calculate the biosequestration value of the campus	Y	Y	University of Michigan Campuses	• Used supervised LU/LC classification on a satellite imagery of the campus and university landholdings, with reference to national inventory data • For natural areas, they used LU/LC data to calculate carbon sequestration potential • For campus, inventory data was used to assess carbon sequestration potential

Table 4: Overview of ES Assessments Under Group 2

Summary of Group 3:

For group 3, there are 16 studies that fall under this category. These studies may either not be conducted for the purpose of advising campus developments or lack concrete recommendations but contain possibly relevant ES assessment methodologies. Among these studies, four of them conducted integrated ES assessments while the rest focused on a single ecosystem service.

Similar to previous groups, all the studies assessed regulating or cultural ES or both. Only one study included provisioning services into its integrated ES assessment (Julian et al., 2018). **Notably, all except two studies conduct their assessment on campus trees or green spaces as ES providers**. This is possibly due to the ease of conducting fieldwork on trees and vegetation as they are immobile and easy to identify.

As for the component of ecosystem services accounted for, only four studies have integrated both demand and supply indicators into their studies while three based their assessment on ES demand indicators while the remaining nine focused on ES supply indicators. Like other groups, cultural ES were predominantly assessed based on ES demand indicators while that of regulating ES were on ES supply indicators. However, there are some exceptions that were featured. X. Wang et al. (2021) have used their tree inventory data together with property prices in order to determine the realised landscape aesthetic ES provided by the trees. Both Y. Wang et al. (2017) and Julian et al. (2018) have used demand indicators through qualitative surveys of students in assessing the perception of regulating ES. **They have shown how the socio-cultural and demographic background of respondents can greatly impact their perception of ES provided and thus this would change the realised value of ecosystem services.** Hence, despite the common focus on either demand or supply for most studies, there is still adequate examples to learn from in terms of integrating both components of ecosystems services into an overall ES assessment.

There are also some key pointers to note from the methodologies adopted by some of these studies**. Firstly Dilaver, Yuksel, and Yilmaz (2017) have illustrated a workaround to the database constraints of using the CTCC in calculating carbon sequestration through categorising local species that do not match with those in the database based on descriptors such as tree type or growth rate.** Afterwards, CTCC species which have similar descriptors would be used as proxies for those in the same category for the analysis. **Secondly, a study by Zambrano, Aronson, and Fernandez (2019) have shown the usefulness of analysing past LU/LC data of a campus in order to determine the evolution of ES provided in relation to campus development**. This analysis would help shape recommendations on future campus ES development plans in hopes of reversing historical devolutions of ES in the campus. **Thirdly, Kong et al. (2016) have supported the use of ENVI-met simulations in visualising the impact of vegetation onto the campus microclimate.** However, they used additional data such as tree height obtained through remote sensing and conducted the simulation on scenarios with and without the green spaces to illustrate impact of vegetation on temperatures. This could be a promising practice adopted in assessing microclimate regulating ES of vegetation.

Title	ES Assessed	ES Provider	Purpose	Dmnd?	Sply?	Study Area	Key Points
Integrating Ecological Objectives in University Campus Strategic and Spatial Planning: a Case Study (Orenstein, Troupin, Segal, Holzer, & Hakima-Koniak, 2019)	Cultural, Regulating ES*	Urban Vegetation and Forests	To identify the priorities of stakeholders in the university on ES and thus how it impacts campus management plans and their ecological considerations	Y	Y	Technion - Israeli Institute of Technology Campus	• ES assessment part of the study but not main focus. • Used ES inventory list to determine presence of ES in campus • Conducted interviews with stakeholders on perception of ES
Urban trees in university campus: structure, function, and ecological values (X. Wang et al., 2021)	Global climate regulation, Local Climate Regulation, Water Flow Regulation, Landscape Aesthetics	Urban Vegetation	Analysing Ecological Benefits and Monetary Value of Urban Trees	Y	Y	Shengyang Institute of Technology Campus	• Use of iTree Streets to calculate benefits of campus trees • Tree diversity to show integrity of ES provided • Age structure to illustrate future potential of tree ES
Geographic Information System-based assessment of mitigating flash-flood disaster from green roof systems (Liu, Li, & Li, 2017)	Water Flow Regulation	Green Roofs	Observe effects of green roofs on urban flood inundation through simulations	N	Y	Deakin University Waurn Ponds	• Usage of complex models to simulate runoff in campus from 10/50-year rainfall events • Simulation repeated with and without proposed green roofs to illustrate its impact on flooding
Public Realm at Qatar University Campus Perception and sustainability of Open Green Spaces (Mogra & Furlan, 2017)	Landscape Aesthetics	Urban Green Spaces	Investigating students' perception of campus open green spaces	Y	N	Qatar University Women's Engineering Campus	• Qualitative survey on perception of green spaces that included landscape aesthetic assessment • No influence of perception on usability of green spaces, but more influenced by microclimate

Thermal Comfort in Urban green Spaces: A survey on a dutch University Campus (Y. Wang et al., 2017)	Thermal Regulation	Urban Green Spaces	Understanding Influence of Urban Green Infrastructure on Outdoor Human thermal comfort level.	Y	Y	University of Groningen Zernike Campus	• Use of onsite climate readings of green spaces and qualitative survey based on thermal comfort and sensation • Found that students' country of origin impacts thermal comfort perception
The Relationship Between Student Use of Campus Green Spaces and Perceptions of Quality of Life (McFarland, Waliczek, & Zajicek, 2008)	Cultural ES	Urban Green Spaces	Finding usage of Green Spaces and their relationship with well being	Y	N	Texas State University-San Marcos Main Campus	• Students who used campus green spaces often perceived their quality of life as higher • Campus green spaces and their availability could influence student retention
Assessment of Carbon Sequestration Potential of Tree Species in Amity University Campus Nodia (Sharma, Pradhan, Kumari, & Bhattacharya, 2020)	Global Climate Regulation	Urban Vegetation	Assessing Total Carbon Sequestration Potential	N	Y	Amity University Campus Nodia	• Use of tree inventory data for assessment • Biomass equations for calculations obtained through past literature
Urban Tree analysis using UAV images and Object-based classification (Wicaksono & Hernina, 2021)	Various ES related to trees	Urban Vegetation	Obtaining urban tree map with canopy cover and LU/LC info	N	Y	University of Indonesia Campus Department of Geography Building	• Possible alternative method to labour-intensive tree inventory compilation in gathering data for tree ES assessments
Assessment of Biodiversity and biomass carbon stock from an urban forest (Khamari, Mansingh, & Pradhan)	Global Climate Regulation	Urban Vegetation	Tree Inventory, check carbon stock	N	Y	Sambalpur University Campus	• Use of tree inventory data for assessment • Biomass equations for calculations obtained through past literature

Estimating Carbon Stock of Live Trees Located on the Main Campus of the University of Georgia (Fox, Dwivedi, Lowe Iii, Welch, & Fuller, 2020)	Global Climate Regulation	Urban Vegetation	Tree inventory and estimate carbon stock	N	Y	University of Georgia Main Campus	• Use of iTree Eco to determine carbon sequestration potential • Species diversity of trees indicated integrity of carbon sequestration ability of the campus trees
Energy Saving Potential of Fragmented Green Spaces due to their Temperature Regulating Ecosystem Services in Summer (Kong et al., 2016)	Temperature Regulation	Urban Green Spaces	Identifying impact of green spaces on microclimate	Y	Y	Nanjing University Gulou Campus	• Use of ENVI-met simulations to simulate microclimate on scenarios with and without green spaces • Tree and building height data obtained through LiDAR • Obtained cooling performance of vegetation through results
Analysis of College Urban Forest Structure Using RS and GIS Technology (Luo, Du, Li, & Xue, 2010)	Unspecified	Urban Vegetation	Analysis of campus forest structure	N	Y	China University of Geosciences West Campus	• Use of fieldwork to compile tree inventory data with parameters such as DBH, health status, crown diameter • Remote sensing techniques to establish digital tree layer for GIS • Species diversity and health of trees measured to indicate integrity of tree ES
Contribution of University Campuses to Climate Change Mitigation: Ankara university Tandogan Campus Case (Dilaver et al., 2017)	Global Climate Regulation	Urban Trees	Calculation of Carbon Sequestered and storage through CTCC	N	Y	Ankara University Tandogan Campus	• Use of CTCC but to resolve mismatch in species database, authors categorised local species based on four descriptors and matched them with species in CTCC database • Suggested tree inventory data to be able to inform landscape management to maximise carbon sequestration potential

Developing General Equations for Urban Tree Biomass Estimation with High-Resolution Satellite Imagery	Various ES related to trees	Urban Trees	Biomass Estimation without needing to conduct physical inventory and relying on a specifically developed allometric equation	N	Y	California State University Fullerton Main Campus	• Use of remote sensing techniques to develop biomass estimations – cross reference with fieldwork conducted on sample of trees
University students' social demand of a blue space and the influence of life experience (Julian et al., 2018)	Various ES related to blue spaces	Blue Spaces	Evaluating social perception of ES provided by San Marcos River	Y	N	Texas State University San Marcos River	• Use of qualitative survey to obtain perception of various ES provided by blue space • Accounting for socio-cultural background and demographics in study – can greatly impact their perception and usage of ES • Practice to better understand students' usage of ES
The Consequences of Landscape Fragmentation on Socio-Ecological Patterns in a Rapidly Developing Urban Area A Case Study of the National Autonomous University of Mexico (Zambrano et al., 2019)	Water flow regulation	Green Spaces	Measure water infiltration and biodiversity changes due to fragmentation of green spaces	N	Y	National Autonomous University of Mexico	• Evaluating evolution of ES through historical data and policies of campus development • Justify need to steer development of campus to reverse the negative changes of ES

Table 5: Overview of ES Assessments Under Group 3

Recommendations

The extensive literature reviewed above has given many insights on how a campus integrated ES assessment framework may look like with different methodologies of conducting ES supply and demand analyse. Studies from group 1 and 2 have shown how ES from different categories can be assessed and integrated to formulate overall recommendations for campus development. Meanwhile, the studies from group 3 have supported some of the ES assessment methods used in the first two groups and have also suggested alternatives or improvements to current methods as well. Overall, the initial list of campus ES assessments obtained have provided substantial information on how the framework of a comprehensive campus ES assessment should look like and possible methodologies to conduct in this assessment. However, there are still certain problems that can be observed from this review:

- Firstly, there is still a lack of campus ES assessments that account for both supply and demand indicators for the different categories of ES. Thus, in attempting to create a state-of-the-art integrated ES assessment framework for NTU, there is still a lack of information on the best practices available from this review.
- Secondly, few studies assessed ecosystems or green infrastructure other than green spaces or urban vegetation. This indicates that other types of green infrastructure may be neglected in current frameworks found.
- And lastly, there has still been little information on how the potential of cultural ES could be measured given the difficult of defining and ascertaining what would be considered as a supply indicator of certain cultural ES. Thus, satisfaction surveys on the stakeholders of the campus would be the main way forward in assessing the campus' available cultural ES.

These problems may be further improved through greater research of studies focusing on these areas, possibly through research conducted beyond campuses and then integrated into a campus context. But as of now, there is adequate information in forming a basic ES assessment framework for the Nanyang Technological University Campus.

<u>Recommendations for Ecosystem Service Assessment for NTU Campus:</u>

When crafting this ecosystem service assessment for NTU, the first step would be to establish the main goals of the assessment. To help the university push towards its sustainability goals, it needs to be able to understand the opportunities and challenges on the campus ability to provide relevant ES to the immediate community and beyond. For that, here are some recommended goals to be set out for this ES assessment:

- Obtaining a list of relevant ecosystem services available in the NTU campus.
- Understanding the constraints faced by ecosystem services in the past, present, and future of campus development.
- Discovering the opportunities to maximise ES in the campus.

Based on these three goals and the findings of the review, this paper has created a proposed workflow as shown in figure 1 for the ES assessment together recommended methodologies for the various stages indicated. This workflow, together with the methodologies proposed, hopefully serves as a foundational framework to be developed on by future research and ES assessment experiences.

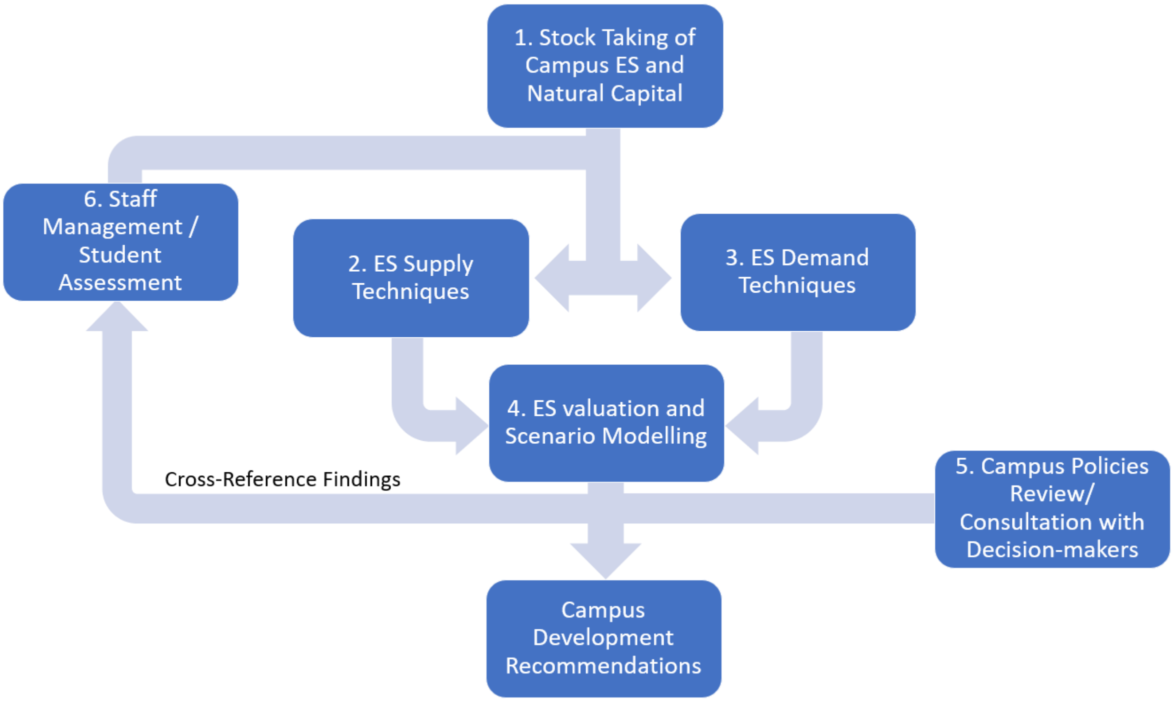

Figure 1: Proposed Workflow for NTU Campus ES Assessment

1. Stock taking of Campus ES and Natural Capital

A. Historical and Present-day LU/LC Classification of NTU

Firstly, LU/LC data of NTU campus should be obtained. This can be done through a supervised machine classification of LU/LC on a satellite image of the campus as demonstrated by Tonietto et al. (2021). The classification could be fine-tuned through cross-referencing with 3rd party LU/LC data of Singapore, either through National Parks (NParks) or databases in data.gov.sg if they exist. Acquiring land cover data would be useful in subsequent stages of assessments such as valuation, scenario modelling, or to aid other ES assessments in stage 2. Additionally, historical LU/LC data could also be obtained in order to understand the evolution of the ES found in the campus. This can be done with reference to historical land use maps of NTU which may be found on government or local university databases.

B. Extensive Tree Inventory Compilation of Campus:

One of the largest groups of ES providers in the campus would be the campus vegetation where many types of ES can be sourced from. Thus, it is important to conduct an extensive tree inventory check of the campus through fieldwork so as quantify the ES related to trees. This importance is highlighted by the many studies as shown in the literature that have conducted such tree inventory compilation. Following the tree inventory process of Cox (2012), all trees within the campus boundaries would be recorded with their genus & species, location, canopy height, DBH and other necessary features. The health status of the trees may be monitored as well, using the method illustrated by Luo et al. (2010) where they used the CITYgreen standard to judge the health of the tree species using indicators like leaf colour or presence of pests. This information may help judge the integrity of the ecosystem services provided and highlight any need for immediate action for campus planning. To acquire manpower for this, students can be employed either as research assistance or through a module where they may learn GIS mapping skills or field research methods as done by Cox. This could be complemented by partnering officials from NParks in order to educate and aid the students and researchers with the identification of trees. The tree inventory data could be compiled into an extensive excel spreadsheet before uploading it as a spatial map through GIS. This map would include shapefile points that contain the coordinates and information of each campus which could be helpful for future campus tree management efforts as what was produced in Cox's tree inventory fieldwork.

C. Recording Green and Blue Infrastructure

Beyond trees, identifying all types of green and blue infrastructure is also important in the campus ES assessments as they also provide a large variety of ES as shown in the review. These could be green roofs or blue spaces that are fitted with park facilities to allow people to enjoy these spaces. To identify the locations of green roofs, they can either be mapped through the LU/LC classification process or through ground observations. Meanwhile, coordinates of campus green and blue spaces could also be recorded on ground and updated to the LU/LC map of NTU. The features of these spaces such as sitting areas may also be noted in order to give greater context on subsequent assessments.

2. ES Supply Assessment Techniques

A. Carbon Storage and Sequestration of Campus Trees:

With the complete tree inventory, the calculation of the carbon storage and sequestration of the campus trees may be done through the use of CTCC as elaborated by Cox (2012) and Dilaver et al. (2017). Using the DBH measurements and the name of the species, the carbon sequestration of each surveyed tree can be calculated by the CTCC through its use of its species-specific growth equations. However, there will be mismatches between the species found in NTU and the species available in the CTCC database. For that, we can refer to Dilaver et al.'s method of matching such species through descriptors can be employed. As for the choice of using the CTCC, it is beneficial in calculating the effect of ES provided for each species and thus the assessment would not only show the total carbon sequestration of all the campus trees but will also illustrate the sequestration potential for each tree in the inventory to better inform campus management and planning efforts.

B. Local Climate Regulating ES Measurements:

As seen by the studies reviewed, campus vegetation and green infrastructure may be significant sources of local climate regulating ES and thus are a subject of interest for those that aim to assess that ES. Following the methods used by Kong et al. and Y. Wang et al., meteorological conditions such as air temperature, solar irradiation, relative humidity, and wind speed on the green spaces that were found in the NTU Campus. This data could either be used to cross-reference against qualitative survey results in both green and grey spaces or used in simulations to estimate their effects onto the campus microclimate.

In the case of simulations, we could refer to the literature by both Wong and Jusuf (2008) and Kong et al. (2016) where ENVI-met simulations were used to determine the overall ambient temperatures of the campus. To assess the impact of vegetation in influencing the campus' ambient temperatures, a modified model of the campus with all the trees and green spaces being replaced by concrete could be constructed as suggested by Kong et al. The simulation could be run again in this setting and a spatial map illustrating the difference in temperatures between these two scenarios could be drafted to clearly illustrate the temperature regulating ES of these vegetation. The reference data for this simulation will be based on the meteorological data obtained on these green spaces.

C. Air Pollutant Filtration of Campus Trees:

In calculating air filtration and runoff reduction ES by these campus trees, we may utilise iTree software to analyse the compiled tree inventory data. As demonstrated by X. Wang et al. (2021), the reduction of air pollutants like nitrogen oxides or particulate matter could be calculated using either default values of the reference city used in the software or historical pollutant levels that may be found on Singapore's meteorological services' databases. Additionally, this data could be cross-referenced and validated through another method of calculating PM10 air pollutant reduction by trees as used by (Nowak, 1994). This method would involve using the Leaf Area Index of trees, possibly obtained through the tree inventory check, and pollutant removal levels of trees of different diameter classes. Although it may be a more extensive process, it would help validate the air filtration estimates obtained from using the iTree software.

D. Runoff Retention of Green Roofs and Water Infiltration Based on LU/LC:

It is important to assess the water infiltration capacity of the campus to understand the possibility of water inundation and stresses to drainage infrastructure during rainstorms. For that, we can take reference to the study by Coskun Hepcan and Hepcan (2018) which uses the LU/LC data and the SCS-CN method in order to determine the water infiltration in the area. Understanding the amount of water infiltrated would help us note the amount of costs saved in drainage treatment by these natural areas (Bouffard et al., 2011). Going further, we may also simulate the potential of flash floods in the area using the simulation methods by Liu et al. (2017) where they used the topographical, watershed, and water infiltration information to simulate flooding or ponding areas from 10-year storm events. This method would also aid in assessing the runoff retention capacity of green roofs as demonstrated by Liu et al. where they modelled the storms under scenarios with and without green roofs. All these information gathered would allow a clear understanding on the strengths and weakness of rainfall regulation in the campus which would thus help advise for more effective recommendations.

E. Cultural ES Supply:

Although cultural ES supply is much harder to identify and assess as compared to the regulating ES supply indicators of the past few steps, it may be possible to have a rough estimate of the overall potential of cultural ES provision. Given that urban trees have an impact to the overall landscape aesthetics, the tree inventory compiled can also be used to indicate the potential of aesthetics ES provided by campus trees. Additional data can also be collected in the tree inventory fieldwork such as presence of flowering trees or shrubs. Interviews can also be conducted on the campus landscape management to determine the maintenance of campus vegetation and green infrastructure. This could serve as another indicator of the potential of aesthetic ES provided by green spaces and infrastructure. Additionally, other features such as nature infographic signboards can be plotted in order to have an indicator of the educational ES supply available.

3. ES Demand Assessment Techniques

A. Qualitative Survey of Campus Users

Previous sections have all assessed the potential ES through supply indicators like the use of the tree inventory or LU/LC data. However, to comprehensively assess the NTU campus' ES, qualitative accounts from stakeholders should be recorded as well to gauge how much of these potential ES is realised and identify demand and supply mismatches so that recommendations can be better crafted. This qualitative study could be designed with reference to Julian et al's survey on the use of blue spaces where students were asked on their ranking of the different types of ES provided by the blue space. Their socio-cultural background and their nature of interaction with the blue space was also recorded to better understand their perception of ES. This method could be replicated in NTU but further expanded to encapsulate more zones of the campus such as green spaces, campus accommodation sites, and other high traffic areas. Additionally, questions on the campus stakeholders' willingness-to-accept or pay may be taken in order to better understand how these perceived ES are valued by the respondents. The qualitative results could then be compared with the assessment results of potential ES to map out areas where there are opportunities for improvements of ES. Understanding the socio-cultural background of the respondents would allow better understanding of the nature of the ES demand by campus users and thus more appropriate recommendations may be crafted.

B. Complementary Surveys for Cultural ES:

Complementing the ES perception surveys done, we could also seek other demand indicators in other to determine the demand for certain cultural ES. For example, to better gauge the appreciation of landscape aesthetics ES of green spaces, a similar method to that of Mt Akhir et al.'s visual quality assessment of TAS could be employed. In this method, photographs of certain green spaces could be taken and edited to remove some of the flowering TAS. The original and edited photos would then be presented to interviewees to rank based on visual quality parameters (Mt Akhir et al., 2020). Comparing the performance of photographs with and without the TAS would give another indicator of the demand for such landscape aesthetic ES on top of the qualitative data obtained.

To gauge the demand for knowledge systems ES, another indicator that can add onto the qualitative data would be to review the module syllabus or environmental education events held in the university. Some modules may require outdoor classrooms and thus by reviewing and noting down the number of modules that utilise the green spaces and vegetation of the campus, we would be able to have a better gauge of the demand for knowledge systems ES.

4. Valuation and Scenario Modelling

A. Benefit Transfer Method of Valuation of Historical and Present-Day ES

With the historical and present-day LU/LC data of the NTU campus obtained in stage one, we would be able to make an estimate on how the ES in the campus have changed over its development as done by both McCoy and Zambrano et al. Using the land cover classification of historical maps, we can use the benefit transfer method in order to evaluate the ES present in the campus throughout the various years of its development. This method would allow us to put a value to the ES found in the campus which we can compare over the years to understand the trends of such ES as the campus develops. The same valuation could be done on the present-day LU/LC data in order to identify ES in the campus that may be important but are currently weakening in provision. This would allow us to focus on crafting recommendations specifically on these ES.

B. Demand-side Indicators Valuation Techniques

The assessment framework so far has provided techniques to accumulate data on both demand and supply indicators for various ES of the campus. We have managed to obtain several ES different valuations of ES so far such as in stage 3 which provides examples of stated or revealed preferences valuation techniques, relying on interviews or survey instruments. Contingent valuation through the perceived ES and willingness-to-accept data may be used to obtain the value of ES as perceived by the stakeholders. This would be especially important for assessing cultural ES as it would be harder to assess its supply indicators due to the difficulty in quantifying it. Also, the productivity method can be used using the data on the number of modules using the surrounding natural spaces and the overall tuition fees of those courses.

C. Supply-side Indicators Valuation Techniques

With all the supply side indicators obtained such as carbon sequestration rates, water inundation rates, and pollution sequestration rates, we may evaluate many of them through referring to market prices. For example, global climate regulation can be evaluated by using carbon market prices and applying it to the amount of carbon sequestered in the campus.

Certain software that was used in quantifying the ES may also be used in valuation. As suggested by Cox, the cooling benefit of trees onto buildings could be calculated through the CTCC and the tree inventory data. The CTCC would be able to generate the estimated energy cost saving based on the position of these trees from such buildings in the NTU campus (Cox, 2012). This would give another indicator on the potential value of the local climate regulation ES of trees.

Once both demand-side and supply-side indicators have been evaluated, they can be compared and interpreted to identify the possible demand and supply mismatches for the ES which can be used, along with other information such as benefit to wellbeing and socio-cultural backgrounds that can be obtained in stage 3, to craft recommendations for ES development in the campus.

D. Scenario Modelling

Once valuation of ES has been conducted and that opportunities and challenges of ES have been identified, we may begin to develop recommendations to develop ES that are valued highly but are found to be weakening in provision due to past campus developments. However, in order to ensure the developed recommendations are effective and suitable for future campus development, we would need to conduct scenario modelling. This can be used to assess the effect of land use or land cover change on the campus which would help shape future masterplans and recommendations by providing spatial, quantitative information on ecosystem services. One simple method that may be adopted could be found under McCoy's study where she has amended the campus' LU/LC map to fit her proposed amendments such as green roofs and pervious roads before evaluating the changes in campus ES through the benefit transfer method. For more specific ES changes, we can look to Liu et al.'s simulation methods where they have set proposed sites of green roofs in order to see its effects on water inundation. Also, following Wong and Jusuf and Kong et al.'s method of using ENVI-met simulations, proposed changes in green spaces and vegetation could be edited virtually into the greenery and tree height data to visualise the impact on the local climate. These practices could aid in finetuning the proposed campus masterplan such that it achieves the sustainability goals of the university.

5. Campus Management and Policy Survey

Before recommendations can be determined, the possible obstacles and additional opportunities needs to be explored through interviews with campus decision-makers. These stakeholders would have a large influence in how future campus development would proceed and thus their interests and views must also be considered to propose ES recommendations that would not only maximise the ES in the campus but also pose minimal conflicts to the current philosophy of

NTU campus’ development. Additionally, current policy restrictions, either from the university body or national regulations, must also be studied to uncover further potential obstacles towards campus ES recommendations.

6, Student Campus ES Assessment Modules

A university module of ES assessment may also aid in the overall campus ES assessment as inspired by Calabria et al. (2011). In this potential module targeted towards graduate studies, they can be taught on the methods to conduct ES assessments such as gathering an overall ES inventory and understanding certain ES concepts before being tasked to create a campus plan for the NTU campus. In the module conducted by Calabria et al., their students were able to construct a comprehensive ES plan of the campus using inventory and stakeholder data. These student campus plans were then compared and discussed to construct an overall development plan that maximises the ES in the campus. In exporting this practice to NTU, this module would be able to provide additional insights and observations that may complement the results of the original ES assessment. Furthermore, having this module conducted regularly in the future may build on the initial ES assessment done by using student data to update the ES inventory of the campus and highlight new challenges and opportunities in ES development that may not have been identified in the initial ES assessment.

Overall, these recommendations are proposed based on the observations identified in the literature of campus ES assessments. This proposal may serve as a base framework for an NTU ES assessment, where new assessment practices and frameworks may be included through futures research.

Appendix

1. Annotated Bibliography

Group 1: Highly Relevant, Integrated Ecosystem Service Assessments

There were 6 studies that fit into the criteria of the first group where an integrated ES assessment is done to advise campus planning. However, half of them were classified under "Detailed" as rank 3, meaning that although these studies may be suitable case studies in forming an ES assessment framework, half of them lack details on how the ES assessment is carried out, making it difficult to fully replicate the assessment process that led to their recommendations.

Focusing on these three detailed studies, two of them assessed urban vegetation and green spaces: An assessment of a Rectorship garden in the Ege University campus (Coskun Hepcan & Hepcan, 2018), and the evaluation of the entire University of Texas Edinburg Campus (Cantu, 2015). Coskun Hepcan & Hepcan used general allometric equations for trees to calculate carbon storage of trees which was then inputted into an equation based on general growth rates of trees to estimate carbon sequestration. These equations were based on past literature that applied to the region. Total runoff in the site was also calculated through the SCS-CN method developed by the United States Department of Agriculture Natural Resources Conservation Service (USDA NRCS). This method utilises variables such as land use/land cover (LU/LC) or soil type to determine volume of runoff in the area (Coskun Hepcan & Hepcan, 2018). This was to determine where stormwater runoff is directed in the garden, whether through soil infiltration or to impervious surfaces. Their ES measurements have allowed them to suggest recommendations to modify the rectorship garden to maximise these ES benefits such as installing detention ponds and rain gardens to provide greater infiltration for the stormwater runoff calculated or how the measurement of carbon sequestration has shown the importance of the garden in managing the campus' carbon footprint.

Meanwhile, Cantu used the program iTree Eco to calculate multiple regulating ES linked to trees including local climate regulation and air quality regulation. The tree data required was collected through a complete tree inventory of the campus, taking note of Diameter at Breast Height (DBH), GPS location, living tree height, and certain tree crown metrics. The study focused on the 15 most abundant species in the campus to determine the ES provision of urban trees in the campus. The valuation of the trees' regulating ES for different species provided several recommendations such as planting certain tree species in specified locations around the campus to maximise the climate regulating benefits near buildings to encourage lower energy use. Also, Cantu suggested that the value calculated through iTree Eco could provide useful information for the campus in informing its insurers of costs of a natural disaster event that damages these trees.

The third study was a honours thesis done by McCoy (2009) which identified the LU/LC of the watershed area in the past and the present of Mullins Creek in the University of Arkansas to calculate the changes in ES value using the Benefit transfer method. This entails referring to past ES assessments done on similar contexts and applying it to an area in order to estimate the value of ES in the area. In McCoy's study specifically, she has referred to literature by Costanza where he had assessed the economic value of ES in different biomes. The author then interpreted the aerial images of the watershed to classify the LU/LC type before assigning these Costanza biomes to them in order to calculate the value of ES in these areas. The author also used a list of ES drafted by Costanza that are to be evaluated by this method. To determine the past LU/LC of the watershed area, historical records were referenced. The valuation of the ES in the watershed was then found by multiplying the area of a biome by its ES coefficient which is based on economic demand and supply indicators (McCoy, 2009). The valuation of ES of the two different time periods were compared to show the changes in ES value.

From that, McCoy found that the present-day conditions value was found to be much less than in the past due to extensive urbanisation of the area. Thus, she suggested improvements that can be made to the area such as green roofs and retrofitting pervious pavements to improve the ES provisions of current impervious urban areas. In order to present her recommendations, she represented areas of pervious pavements and green roofs as 50% of the services of a grass/rangeland biome. She displayed a 7% gain in ES through the same valuation method. However, she also noted that the monetary cost of implementation would be far greater than the increase in service value.

Meanwhile for the less "Detailed" ES studies, they do offer useful insights on how the overall framework of ES assessments should look like. The Yale's Central Campus ES assessment was split into three phases: the conceptual assessment to examine the social patterns of the campus to understand the spatial nature of ES demand, the ES assessment where biophysical indicators were observed to understand the degree of ES provided, and the Social Dynamics assessment where campus stakeholders were interviewed to understand the social perception of ES (Bouffard et al., 2011). This allowed the campus planners to understand the opportunities to maximise ES provision and the potential challenges that may arise from such improvements so that recommendations on campus development can be crafted to fit these challenges and opportunities. As for the Yale's Medical Campus ES assessment, they followed a similar structure with that of Central Campus except that the opportunities of ES improvements seemed to be found through general observations rather than any recording of specific biophysical indicators. They have also used case studies of other universities to supplement the ES observations to justify the recommended changes.

One interesting study to note would be Calabria et al. (2011) where instead of a deliberate ES assessment of the campus area, the writers have included it as a learning activity for graduate students where they assessed the ES of the campus and provide recommendations for future campus development. The assessment was done in 3 stages: studying policy regulations and case studies, conducting stakeholder input sessions, and conducting an ES inventory check. Examples of metrics recorded for the ES inventory check were volume of stormwater runoff infiltrated on-site, area of native vegetation, site imperviousness, floodplain storage provided, and species diversity. The inventory data was then analysed to determine if certain areas may or may not support planning goals. Hubs and linkages of ES were also identified to propose opportunities to recreate or connect these areas. These are patches or corridors respectively in the landscape that support ecological functions. Afterwards, these data were used to create a campus plan focused on a timespan of about 2 generations later which is deemed enough buffer time for the students to reconfigure the existing buildings and associated grey infrastructure (Calabria et al., 2011).

Group 2: Highly Relevant, Single-ES Assessments

There were 5 articles fall under the second group where they are considered "Relevant" but not "integrated" ES assessments. All of them have found to be very "detailed" with them classified under rank 3.

There were two that measured carbon sequestration of the campus urban trees; however, different methods were used. Cox (2012) did a complete tree inventory check, recording their species, location, DBH and computing them into the Centre of Urban Forest Research Tree Carbon Calculator (CTCC). This program allows the author to determine the carbon sequestration benefit for each individual tree and thus the overall carbon sequestration for the campus urban trees. The author noted that advantage of CTCC over other programs such as iTree eco was to allow her to assess the carbon storage sequestration potential provided for each tree. A full spatial map of the campus trees was then created and given to the campus management for their reference (Cox, 2012).

Meanwhile, Tonietto et al. (2021) did their carbon sequestration assessment through remote sensing. Using the satellite imagery, supervised machine classification of LU/LC was done. The product was then adjusted using additional land-use data provided by the United States Fish and Wildlife Service NWI. For the university's natural areas, the range of carbon storage and sequestration was multiplied by the total area of the LU/LC type to estimate the range of total carbon storage and sequestration. However, for the campuses itself, they used tree inventory data instead to get a better carbon sequestration estimation. This is due to how urban trees are much easier to quantify than the natural areas. The carbon sequestration results were used to justify the preservation of natural areas of the campus and support continual land management to expand bio-sequestration potentials. General valuation of other ES was done using the benefit transfer method and the LU/LC data. However, as this was not the main focus of their study, it would not be considered as an integrated ES assessment.

The other studies in this group has also given greater insights on examining ES that were not covered in group 1. Wong and Jusuf (2008) have assessed the local climate regulating effect of urban trees in the National University of Singapore campus through ENVI-met simulations. They have compared ambient temperatures of the campus between the current scenario, the 2005 campus master plan, and that with increased trees. Simulations showed that temperatures would be higher than current conditions with the 2005 master plan, even with increased trees due to the decrease in greenery rate. This has allowed them to justify recommendations such as installing more green roofs on newly constructed buildings or install grass patches near buildings which they have shown to significantly increase the greenery rate of the campus.

Mt Akhir et al. (2020) have illustrated the aesthetic effect of trees and shrubs (TAS) where they have asked students to rank photographs based on landscape parameters such as visual preferences and vividness. The photographs were of selected green spaces in the campus and their duplicates where some TAS were edited out. They have found that respondents gave high scores for the original photographs that feature the existing TAS. Hence, they conclude that the high visual quality reflected by TAS, recommending future plantation designs in the campus to integrate dendrologic characteristics of TAS.

Addas and Maghrabi (2021) have examined the impact of public open spaces (POS) in the King Abdulaziz University Campus on the well-being of stakeholders through a questionnaire asking on the perceived importance of POS services such as recreational or leisure and how they have affected their well-being. They then found that most respondents were aware of such services and that educational value was ranked highest followed by sense of place (Addas & Maghrabi, 2021). However, the perceived importance of ES has also been found to be impacted by the socio-demographic attributes of the stakeholders. From these findings, they have proposed a conceptual framework for the management of the campus POS to improve the functional value of its services.

Group 3: Methodologically Relevant ES Assessments

For group 3, there are 16 studies that fall under this category. These studies may either not be conducted for the purpose of advising campus developments or lack concrete recommendations, however, their ES assessments methods are relevant such that they can contribute to the formation of a robust campus ES assessment framework. Among these studies, four of them conducted integrated ES assessments while the rest focused on a single ES. Only one was relatively sparse in their details, which is the study by Orenstein et al. (2019), ranking 2 under the "detailed" category. This study would not be thoroughly analysed due to the lack of information available.

Notably, half of the detailed studies have conducted some form of tree inventory check fieldwork in their assessment of ES provided by trees, likely due to the ease of identifying and measuring its indicators as compared to other ES like water infiltration or cultural ES. However, in data collection, these studies have come up with different methods such as the extensive fieldwork data collection (Dilaver et al., 2017; Fox et al., 2020; Luo et al., 2010; Sharma, Pradhan, Kumari, & Bhattacharya, 2021; X. Wang et al., 2021; Wu, 2019), quadrat sampling of locations to be studied (Khamari et al.), and remote sensing through Unmanned Aerial Vehicle (UAV) or satellite imagery (Wicaksono & Hernina, 2021; Wu, 2019). These studies have illustrated the trade-offs between accuracy and cost in collecting tree biophysical data where an extensive tree inventory fieldwork would provide the most accurate results but at a high manpower and time costs while remote sensing and classification would offer the lowest costs but the lowest accuracy.

One key observation on the studies that have conducted a tree inventory check would be that many of them have also recorded structural features such as the age of the trees, the species diversity, and the health of the trees. Although they may not be used to assess the provision of ES, these indicators are used to show the stability and potential of the campus trees in providing the overall ES. For example, low species diversity was highlighted to be a threat in the ability to provide ES as the campus trees would potentially be more affected by diseases.

Meanwhile, in the assessment of ES provided by trees based on the data collected, some studies used allometric equations found either through past literature or through fieldwork (Khamari et al.; Sharma et al., 2021; Wu, 2019), while others used software such as iTree or CTCC (Dilaver et al., 2017; Fox et al., 2020; X. Wang et al., 2021). The difference in assessment methods could be due to how software like iTree and CTCC are region specific, as highlighted earlier, and thus in some regions, they may opt to use allometric equations that are specific to their regions. However, as demonstrated by Dilaver et al., tree species in the region could be matched with similar species in the database in terms of tree type and growth rate so that those recognised species could be used as proxies when using the CTCC. Also, X. Wang et al. has shown how the iTree program could be used to assess a multitude of ES provided by trees such as air pollution, and aesthetics using demand indicators as well. Thus these software may prove to be useful even in unsupported regions.

As for the other half of the studies, there were a variety of ES assessed from different providers like green or blue spaces. Two of them focused on cultural ES of green spaces, using questionnaires to gather data for assessment (McFarland et al., 2008; Mogra & Furlan, 2017). Mogra & Furlan surveyed the respondents' perception and awareness of these green spaces. Identifying the relationship between these two would help them understand the nature of the demand of ES provided by these green spaces and thus help plan policies to maximise the use of cultural ES. In this case, Mogra & Furlan found that there was no influence of perceived ES on the use of green spaces but rather the climatic conditions. McFarland, Waliczek, & Zajicek's study zeroes in on how green spaces has impacted the well-being of students in the university. They have found that there is a positive relationship between the use of campus green spaces and their perceived quality of life. Although the focus was not directed as an ES assessment, well-being may be a suitable indirect indicator of the demand for ES provided by these green spaces especially if the survey was paired with questions about the type of usage of these green spaces.

Another ES assessed was thermal regulation by green spaces. Both had vastly different approaches in representing the thermal regulating impact of green spaces in campuses. Y. Wang et al. (2017) have investigated the supply and demand of thermal ES through measuring the microclimate on these green spaces and surveying students' thermal comfort and sensation. Additionally, they have also recorded the respondents' non-physical and personal factors and found them to have greatly impacted their perceived thermal comfort. This shows the necessity of using both environmental and subjective factors in assessing the thermal regulation ES of green spaces for campus microclimate regulation. Meanwhile, Kong et al. (2016) used ENVI-met simulations instead to illustrate the cooling effect of green spaces by constructing scenarios of campuses with and without such green spaces. This approach focuses on the supply indicators which are the presence of green spaces and this it may synergise with Y. Wang et al.'s thermal comfort survey to give a more comprehensive assessment on thermal regulation ES.

There are two studies in this group that assessed the rainfall runoff regulation ES, one specifically on the runoff retention of green roofs (Liu et al., 2017), and another based on the changes in water infiltration through examining the historic LU/LC of the campus (Zambrano et al., 2019). Liu et al.'s study was to model the effects of green roofs being placed in the Deakin University Waurn Ponds campus on the expected flooding in the area. They have found them to be significant in mitigating flooding by common storm events but can only manage to reduce ponding areas for severe storm events. This methodology can be useful in simulating the effects of existing green roofs in the setting of NTU and thus show areas where water inundation would be high. As for Zambrano et al.'s study, they have done LU/LC classification on of past historical maps till present to identify the fragmentation of natural spaces and the impacts of its ES provision. Understanding this evolution would help them recommend policies for the campus to work towards protecting these spaces and reversing such changes in future developments. This methodology could be useful in not only on understanding the changes of ES provision through the development of the campus but also to complement studies on runoff retention of green roofs to synergise both green roofs and natural spaces to maximise rainfall runoff regulation in the campus.

Lastly, there is one study by Julian et al. (2018) that conducted an integrated ES assessment specifically on the campus main blue space: the San Marcos River. Their study takes a demand-side approach in assessing the river's ES. They conducted surveys on the student population on their usage and perceived importance of the ES provided by the blue space. This has allowed the authors to understand the types of ES in demand by students and how their socio-cultural background has impacted such views. The information was suggested to help fine tune on-campus ES management efforts such that they are more suited to its users' demands. Hence, the design of the survey can be noted in collecting information on the demand of ES by the students in campuses.

2. List of ES definitions, Indicators, Components, and Characteristics for Reference as Compiled by Burkhard et al. (2014)

Regulating ecosystem service	Definition	Exemplary Service potential indicators	Exemplary Service flow indicators	Exemplary Demand indicators*	Exemplary Service providing units (SPU) (hotspots)	Exemplary Service benefitting areas (SBA)	SPU - SBA spatial relations	Rival	Spatial assessment scale	Temporal scale (hot moments)
Global climate regulation	Long-term storage of potential greenhouse gases in ecosystems.	Amount of methane, carbon dioxide and water vapour stored in vegetation, soils and marine systems (t C/ha)	Amount of methane, carbon dioxide and water vapour taken up by vegetation, soils and marine systems (t CO_2/ha per year)	Greenhouse gas emissions by industry, traffic, households (t CO_2/ha per year)	Soils, forests (standing biomass), peatlands, oceans	The world, climate change-affected regions, agriculture	In situ, omni-directional	Yes	Global, continental	Long-term
Local climate regulation	Changes in local climate components like wind, precipitation, temperature, radiation due to ecosystem properties.	Temperature (°C); albedo (%); precipitation (mm); wind (Bft); evapotranspiration (mm); shaded areas (ha; %)	Temperature amplitudes (K); precipitation, wind or evapotranspiration deviation from surrounding areas (%)	Excess heat, rain or storm performance (°C, mm. Bft) or periods (d/a); Air conditioning use (kWh/a)	Forests, wetlands, lakes, oceans, (urban) green areas, air-circulation corridors	Residential and recreation areas	In situ, omni-directional, directional	No	Local, regional	Medium-term, annual, seasonal
Air quality regulation	Capturing/filtering of dust, chemicals and gases from air.	Leaf area index, difference between open land and throughfall deposition (kg/ha); immission concentrations (ppm)	Aerosols or pollutants removed (kg/ha per year); air quality standards amplitudes (ppb)	Level of pollutants in the air (ppb); air quality standards deviation (ppb); critical loads exceedance (kg/ha per year)	Woods, hedges, green areas	Residential and recreation areas	In situ, omni-directional, directional	No	Local, regional	Medium-term, annual, seasonal
Water flow regulation	Water cycle feature maintenance (e.g. water storage and buffer, natural drainage, irrigation and drought prevention).	Water storage capacity (m^3/ha); groundwater recharge rate (mm/ha per year)	Water released for hydrological process use, e.g. plant or animal uptake, soil processes (m^3/ha per year); available water content (v%);amount of excess water (m^3/ha per year)	Periods at permanent wilting point (d/a); soil field capacity (v%); periods of excess water or floods (d/a)	Water bodies, wetlands, forests, glaciers	Agricultural areas, residential areas, industrial areas	In situ, omni-directional, directional	Yes (agri-culture) No (floods)	Regional	Medium-term, annual, seasonal
Water purification	Ecosystem ability to purify water, e.g. from sediments, pollutants, nutrients, pesticides, disease-causing microbes and pathogens.	Water quality indicators: sediment load (g/l); total dissolved solids (mg/l)	Elements removed from water (kg/m^3 per year); water quality standards amplitudes (ppb; mg/l)	Level of pollutants in the water (ppb); water quality standard deviation (ppb; mg/l)	Water bodies, aquatic flora, riparian strips, filtrating soils, forests, wetlands, grasslands	Residential or recreation areas, agriculture, industry	In situ, omni-directional, directional	Yes	Local, regional, catchment	Medium-term, annual, seasonal
Nutrient regulation	Ecosystem ability to recycle nutrients, e.g. N, P.	Nutrient turnover rates of, e.g. N, P (y^{-1}); water quality indicators, e.g. N (mg/l), P (mg/l); electrical conductivity (µS/cm); total dissolved solids (mg/l); soil potentials (CEC; SOC; texture)	Nutrients available for plant uptake (kg/ha per year); amount of excess nutrients (kg/ha per year); nutrients filtered or adsorbed (kg/ha per year)	Periods of nutrient deficit or excess (d/a); fertilizer needs (kg/ha per year); periods of eutrophication (d/a)	Forests, grasslands, wetlands, marshes, water bodies, oceans	Agricultural areas, communities	In situ, omni-directional, directional	Yes	Local, regional, catchment	Medium-term, annual, seasonal
Erosion regulation	Soil retention and the ability to prevent and mitigate soil erosion and landslides.	Vegetation cover (%); loss of soil particles by water and wind (kg/ha per year); USLE factors for assessment of potential soil loss and landslide frequency (n/ha per year)	Amount of soil retained or sediment captured (kg/ha per year); amount of prevented erosion events (n/a)	Number of erosion events (n/ha per year); soil loss by erosion (kg/ha per year)	Forests, hedges, groves around and between acre fields, pastures, grasslands	Agricultural fields, infra-structure, residential areas	In situ, omni-directional, directional	No	Local, regional	Short-term (events), long-term (regulation)

Erosion regulation	Soil retention and the ability to prevent and mitigate soil erosion and landslides.	Vegetation cover (%); loss of soil particles by water and wind (kg/ha per year); USLE factors for assessment of potential soil loss and landslide frequency (n/ha per year)	Amount of soil retained or sediment captured (kg/ha per year); amount of prevented erosion events (n/a)	Number of erosion events (n/ha per year); soil loss by erosion (kg/ha per year)	Forests, hedges, groves around and between acre fields, pastures, grasslands	Agricultural fields, infra-structure, residential areas	In situ, omni-directional, directional	No	Local, regional	Short-term (events), long-term (regulation)
Natural hazard protection	Protection and mitigation of floods, storms, fires and avalanches.	Water-storage potential (m^3/ha); natural barriers (dunes, mangroves, wetlands, coral reefs, forests) (%; m/ha; ha)	Number of prevented hazards (n/a); Prevented fatalities, damage to property or infrastructure (n/a; €/a)	Number of hazards and fatalities (n/a); damage costs (€/a)	Forests, mangroves, beaches, coral reefs, wetlands, water bodies	Built areas, land uses, infra-srtucture and industry within hazard-prone zones	In situ, omni-directional, directional	No	Local, regional	Short-term (events), long-term (regulation)
Pollination **	Bees, birds, bats, moths, flies, wind, non-flying animals contributing to pollen transfer and reproduction of plants.	Species numbers and amount of pollinators (n/ha); potential habitats for pollinators (ha/ha; %; n/ha)	Amount of pollinated plants (n/ha per year; %/a; kg/ha per year)	Amount of agricultural, garden or wild plants demanding pollination (n/ha per year; %/a; kg/ha per year)	Gardens, fruit and berry plantations, forests, wetlands, agricultural areas	Agricultural, garden and wild plant areas, fruit tree plantations, farmers	Omni-directional	No	Regional	Annual
Pest and disease control**	Ecosystem ability to control pests and diseases due to genetic variations of plants and animals making them less prone to diseases and actions of predators and parasites.	Populations of biological disease and pest control agents (n/ha); Potential habitats for control agents (ha/ha; %; n/ha)	Number of prevented pest and disease outbreaks or predator and parasite actions (n/ha per year; %/a)	Number of pest and disease outbreaks (n/ha per year); Plants and animals damaged (%/a; n/a); Yield losses (%/a; €/a)	Forests, wetlands, water bodies, gardens, agricultural areas	Com-munities, transport facilities, agricultural fields, farms, stables, crops, animals, farmers	In situ, omni-directional, directional	No	Local, regional	Annual, long-term
Regulation of waste**	Ecosystem ability to filter and decompose organic material in water and soils.	Amount and number of decomposers (n/ha); immobilization potential in plants and soils	Decomposition rate (kg/ha per year); Pollutants recycled or Immobilized (kg/ha per year)	Level of organic material in water and soils (ppb); environmental standards deviation(ppb)	Soils, forests, pastures, wetlands, water bodies, oceans	Com-munities, industry, dump sites, agriculture	In situ, omni-directional, directional	Yes	Local, regional	Annual, long-term

* Demand for regulating ecosystem services is problematic to indicate because direct ecosystem service-human benefit relations are often very complex. Indicators suggested here relate to relevant ecosystem states or regulating processes instead. The demand is mostly oriented toward a reduction of the indicator values or the indicating concentrations.

** For these ecosystem services a strong overlap with ecosystem functions and a high potential of double-counting must be noted.

Table 6: List of Regulating ES and its Definitions, Indicators, and Components (Burkhard et al., 2014)

Provisioning ecosystem service	Definition	Exemplary Service potential indicators	Exemplary Service flow indicators	Exemplary Demand indicators	Exemplary Service providing units (SPU) (hotspots)	Exemplary Service benefitting areas (SBA)	SPU - SBA spatial relations	Rival	Spatial assessment scale	Temporal scale (hot moments)
Crops	Plants usable for human nutrition.	Standing stock +/or net primary production (t C/ha + t C/ha per year; kJ/ha + kJ/ha per year)	Harvested crops (t/ha per year, kJ/ha per year); Yield (€/ha per year)	Crop product consumption (kg/person per year; kJ/person per year)	Agricultural fields, gardens, fruit and berry plantations	Farms, food industry, communities, households	Decoupled	Yes	Regional, local	Annual, seasonal, short-term (harvest rhythm)
Biomass for energy	Plants usable for energy conversion (e.g. sugar cane, maize).	Standing stock +/or net primary production (t C/ha + t C/ha per year; kJ/ha + kJ/ha per year)	Harvested plants (t/ha per year, kJ/ha per year); Yield (€/ha per year)	Energy use based on biomass (kWh/person per year)	Agricultural fields, short rotation coppice, oceans	Farms, industry, communities, households	Decoupled	Yes	Regional, local	Annual
Fodder	Nutritional substances for domestic animals.	Standing stock +/or net primary production (t C/ha + t C/ha per year; kJ/ha + kJ/ha per year)	Fodder plant harvest (t/ha, kJ/ha per year); Yield (€/ha per year); Area used for harvesting fodder (ha)	Fodder use for domestic animals (kg/livestock per year)	Graslands, pastures, agroforestry, marshlands	Farms, stables, pastures	Decoupled	Yes	Regional, local	Annual
Livestock (domestic)	Domestic animals useable for nutrition and related products (dairy, wool).	Number of animals (n/ha; kJ/ha); Animal production (t C/ha per year; kJ/ha per year)	Respective animal products (t/ha per year); Yield (€/ha per year)	Meat consumption (kg/person per year); Related products consum-ption (kg/person per year)	Pastures, farms, stables, grassland, agroforestry	Farms, communities, households	Decoupled	Yes	Regional	Annual
Fibre	Natural fibre (e.g. cotton, jute sisal, silk, cellulose) usable for e.g. cloths, fabric, paper.	Biomass +/or growth of fibre (t/ha + t/ha per year)	Harvested fibre (t/ha per year; kJ/ha per year); Yield (€/ha per year)	Fibre use (t/region per year)	Agricultural fields, farms, natural vegetation	Farms, industry, construction, communities, households	Decoupled	Yes	Regional	Annual
Timber	Wood useable for human purposes (e.g. construction).	Standing stock +/or net primary production (t C/ha + t C/ha per year; kJ/ha + kJ/ha per year)	Harvested wood (solid m³/a; volume/a); Yield (€/ha per year)	Timber use (t/region per year)	Forests, silvicultural areas, fruit and berry plantations, agroforestry	Forester, sawmills, wood industry, construction, communities, households	Decoupled	Yes	Regional, local	Long-term
Wood fuel	Wood suitable for energy conversion and/or heat production.	Standing stock +/or net primary production (t C/ha + t C/ha per year; kJ/ha + kJ/ha per year)	Harvested wood fuel (m³/ha per year); Yield (€/ha per year)	Wood used as fuel (m³/person per year)	Forests, short rotation coppice, hedgerows, agroforestry	Forester, industry, communities, households	Decoupled	Yes	Regional, local	Medium-term
Fish, seafood and edible algae	Seafood, algae useable for food, fish meal and fish oil.	Fish stock +/or growth (t C/ha + t C/ha per year; kJ/ha + kJ/ha per year)	Caught fish/seafood/algae (t/ha per year, kJ/ha per year); Yield (€/ha per year)	Seafood/algae consumption (kg/person per year)	Water bodies and courses, coastal lagoons, oceans	Fishermen, food industry, communities, households	Decoupled	Yes	Regional, local	Medium-term
Aquaculture	Seafood/algae in marine and terrestrial aquaculture farms.	Animal stock +/or growth (t C/ha + t C/ha per year; kJ/ha + kJ/ha per year)	Harvest of seafood/algae (t/ha per year, kJ/ha per year); Yield (€/ha per year)	Aquaculture product consumption (kg/person per year)	Aquaculture farms, fish ponds, water bodies, rice fields, coastal lagoons, estuaries, oceans	Fish farmer, food industry, communities, households	Decoupled	Yes	Local	Medium-term, annual

Wild food, semi-domestic livestock and ornamental resources	Berries, mushrooms, (edible) plants, wild animals, fish and natural ornaments available for recreational fishing, hunting or collection; semi-domestic animal husbandry.	Amount of respective items available; stock +/or growth of respective wild species (n/ha; kg/ha; kg/ha + kg/ha per year; kJ/ha + kJ/ha per year)	Catch of fish; game taken (kg/ha per year); Harvested plant biomass (t C/ha per year); Yield (€/ha per year)	Wild food consumption (kg/person per year); Ornamental item sale (n/region per year); Business volumes (€/a)	Forests, grasslands, agricultural fields, water bodies and courses, mountains	Forester, hunter-gatherers, angler, herder, industry, communities	Decoupled	Yes	Local, regional	Annual
Biochemicals and medicine	Natural products useable as biochemicals, medicine and/or cosmetics.	Amount or number of substances useable for medicine, biochemical, cosmetics (kg/ha; n/ha); Stock +/or net primary production (t C/ha + t C/ha per year; kJ/ha + kJ/ha per year)	Yield of respective products (€/ha per year)	Substances used (kg/ha per year); Products sale (€/region per year)	Forests, gardens	Gatherer, gardener, pharmacy, beauty industry, consumer	Decoupled	Yes	Local, regional	Annual
Freshwater	Fresh and process water available for e.g. drinking, domestic use, industrial use, irrigation.	Fresh- and/or process water availability (l/ha per year; m^3/ha per year); Total amount of water (m^3/ha); Groundwater recharge rate (m^3/ha)	Water withdrawal (l/region per year; m^3/region per year)	Water use (l or m^3 /person per year; l or m^3/industrial sector per year)	Water reservoirs, water bodies and courses, glaciers, groundwater	Water supply companies, agriculture, industry, communities, households	In situ; directional; (decoupled)	Yes	Local, regional	Annual, medium-term
Mineral resources***	Minerals extractable close from surface or above surface (e.g. sand for construction, lignite, gold, salts).	Minerals available for extraction (t/ha)	Excavated minerals (t/ha per year); Earnings (€/a)	Minerals used (t/person per year; t/industrial sector per year)	Coal beds, ore veins, moraines, eskers, sea bed, salines	Mining companies, industry, construction, communities, households	Decoupled	Yes	Local	Annual, long-term
Abiotic energy sources***	Abiotic energy sources useable for conversion (e.g. solar, wind, water and geothermic power).	Areas and natural settings potentially suitable for energy conversion (ha/ha; n/ha; GW/ha)	Converted energy (kWh/ha per year); Produced electricity (kWh/ha per year); Yields (€/ha per year)	Energy use (kWh/person per year; kWh/industrial sector per year)	Open spaces on- and offshore, water bodies, geothermal fields	Wind or solar farmer, energy companies, communities, households	Decoupled (electricity); in-situ (water mill; geothermic)	No	Local, regional	Annual

*** Abiotic outputs from natural systems (after CICES); often not acknowledged as ecosystem services, but of high relevance for policy decisions and land use/resource management.

Table 7: List of Provisioning ES and its Definitions, Indicators, and Components (Burkhard et al., 2014)

Cultural ecosystem service	Definition	Exemplary Service potential indicators	Exemplary Service flow indicators	Exemplary Demand indicators	Exemplary Service providing units (SPU) (hotspots)	Exemplary Service benefitting areas (SBA)	SPU - SBA spatial relations	Rival	Spatial assessment scale	Temporal scale (hot moments)
Recreation and tourism	Outdoor activities and tourism relating to the local environment or landscape, including forms of sports, leisure and outdoor pursuit.	Number of facilities (e.g. hotels, restaurants, hiking paths, parking lots; n/ha); Results from questionnaires on nature and leisure preferences (wildlife-viewing, hiking, fishing, sports)	Number of facility visitors (n/facility per year); Turnover from tourism (€/ha per year)	Results from question-naires on holiday plans and expectations	Forests, water bodies, beaches, mountains, urban green, gardens, leisure facilities	Touristic infrastructure, visitors, communities, households (at home location)	In situ, omni-directional, directional, decoupled	De-pen-ding on visitor car-rying capa-city	Local, regional	Seasonal, annual
Landscape aesthetic, amenity and inspiration	Visual quality of the landscape/ecosystems or parts of them influencing human well-being and the need to create something as well as the sense of beauty people obtain from looking at landscapes/ecosystems.	Evaluations from questionnaires; Scenic beauty estimation via landscape metrics	Number of paintings/illustrations, songs, products portraying the resp. landscape/ecosystem (n/landscape type); results of travel cost or willingness to pay estimations	Results from question-naires on landscape preferences and expectations	Viewsheds, seascapes, water bodies and courses, forests	Touristic infrastructure, trader, industry, visitors, communities, households (at home location)	In situ, omni-directional, directional, decoupled	No	Regional	Seasonal, annual
Knowledge systems	Environmental education based on ecosystems/landscapes and knowledge in terms of traditional knowledge and specialist expertise arising from living in this particular environment.	Number of environmental educational-related facilities (n/ha)	Number of environmental educational-related events and number of their users (n/a)	Requests for environment al education (n requests/a)	Geotopes, traditional land use systems, forests	Education facilities, research, industry, visitors, households (at home location)	In situ, decoupled	No	Regional - global	Medium-term, long-term
Religious and spiritual experience	Spiritual or emotional values that people or religions attach to local ecosystems or landscapes due to religious and/or spiritual experience.	Number of spiritual facilities or items (n/ha)	Number of visitors of spiritual facilities or items for performance of rituals and maintain the relationship with ancestors (n/facility per year)	Requests for religious and spiritual experience (n requests per year)	Forests, trees, water bodies, rocks, graveyards	Spiritual facilities, visitors, households (at home location)	In situ, decoupled	No	Regional	Seasonal, annual
Cultural heritage and cultural diversity	Values that humans place on the maintenance of historically important (cultural) landscapes and forms of land use (cultural heritage).	Areas and natural settings potentially suitable for traditional land use (ha/ha; n/ha); Results from question-naires on local people's personal preferences	Number of traditional land use forms (n/ha); Number of employees in traditional land use forms (n/ha)	Number of job appli-cations and trainees in traditional land use forms (n/a)	Agricultural fields, gardens, vineyards, terraced fields, hedgerows, silviculture, villages	Traditional land use regions, visitors, households (at home location)	In situ, decoupled	No	Local - Global	Long-term
Natural heritage and natural diversity	The existence value of nature and species themselves, beyond economic or direct human benefits.	Potential habitats for endangered, protected and/or rare species (n/ha)	Abundance of endangered, protected and/or rare species (n/ha)	Relevant guidelines for nature protection (n/ha)	Natural forests, peatlands, water bodies and courses, mountains	Nature itself, households (at home location)	In situ, decoupled	No	Regional - global	Long-term

Table 8: List of Cultural ES and its Definitions, Indicators, and Components (Burkhard et al., 2014)

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