An ecosystem service value chain analysis framework: a conceptual paper

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Abstract

Modern day societies and economies are becoming increasingly vulnerable to the continued erosion of the stocks and flows of essential ecosystem services. Thus, the management of complex socio-economic systems to effectively provide these essential services has become a global priority policy and academic research area. Understanding how underlying processes and functions contribute towards the provision of final ecosystem services can facilitate improved dissemination of credible, legitimate and salient information to decision-makers. This paper presents an ecosystem service value chain analysis framework that applies basic system dynamics modelling in the form of causal loop diagrams to facilitate value chain analyses for final ecosystem services. A scoping application of the framework is applied to a case study for flood attenuation services in the Baviaanskloof catchment in South Africa. The framework enables the identification of forward linkages and ripple effects in individual value chains of final ecosystem services as well as the identification and assessment of challenges and opportunities within individual value chains. Ultimately, providing the potential to advance strategies for improving the efficiency and effectiveness of final ecosystem service provision.

Keywords: ecosystem services, value chain analysis, causal loop diagram.

Highlights

- An iterative framework for conducting qualitative and quantitative value chain analyses for ecosystem services is proposed.
- A qualitative scoping application of the framework is applied to a case study focused on flood attenuation as a final ecosystem service.
- The framework facilitates the identification of forward linkages and ripple effects within individual value chains and effectively enables the assessment of opportunities and threats.
- Providing the potential to advance strategies and management focused on improving ecosystem service provision.

1. Introduction

Modern day societies and economies are becoming increasingly vulnerable to the continued erosion of the stocks and flows of essential ecosystem services (ESs) (De Groot *et al.*, 2010a; Vihervaara *et al.*, 2010). The inherently conflicting nature of economics and ecology provide complex, transdisciplinary and multi-scalar management challenges faced with ever increasing economic costs of inaction (Stern, 2007; TEEB, 2010). Since the 1970s, the development of the ES concept has brought about a myriad of ES management approaches (Gómez-Baggethun *et al.*, 2010), yet traditional neoclassical market structures and processes continue to underprovide ESs (Boyd and Banzhaf, 2007; Hanley *et al.*, 2007) due to their lack of integration into formal markets, the limitations of ES valuation and perverse incentive structures around the provision of certain ESs. Thus, providing incentive to develop transdisciplinary tools focused on bridging the gap between ES valuation and practical, sustainable ES management.

Global recognition of the economy as a sub-system of the environment and rigorous scientific research in ESs is in its infancy and, thus, robust means for modelling, mapping, valuing and measuring ESs are non-existent and/or not widely debated (Costanza, 2008; Fisher *et al.*, 2009; Rockström *et al.*, 2009). New schools of thought purporting the interconnectedness and co-dependencies of environmental sustainability and social justice (Raworth, 2017) further emphasise the importance of holistic socio-ecological frameworks for ES management to be able to reconcile the incongruity between ecology and economics (Gómez-Baggethun and Barton, 2012).

John Stuart Mill (1882), in his famous book *A System of Logic*, first posited the notion of inductive inquiry, which structures any analysis of things in the natural science domain according to their individual components. Understanding intricate socio-ecological systems requires a clear definition of key system components and their associated cause and effect relationships as well as a description of the relationship of the system to other systems (De Groot *et al.*, 2010b; Ford, 1999; Limburg *et al.*, 2002). Complexity is a characteristic common to all coupled human-environment systems (Loehe, 2004) and thus the challenge to communicate the functionality of such systems lies within explaining the relationships between key elements of the system in a simple and transparent way.

This paper presents and critically analyses an ecosystem service value chain analysis (ESVCA) framework that applies basic system dynamics modelling in the form of causal loop diagrams

(CLDs) to facilitate value chain analyses for final ESs. The notion of value chain analysis and the concept of CLDs as a modelling tool are discussed in relation to ES theory and management. We present a detailed step-by-step development of the ESVCA method and outline a scoping application in South Africa. Lastly, the strengths and limitations of the approach are discussed alongside directions for future research.

2. Value Chain Analyses

Traditionally, value chain analyses trace the value being added in each step in the life cycle of a particular good or service, from the process of production/harvesting through various steps of value adding until final consumption or utilisation and waste disposal (Baleta and Pegram, 2014; Kaplinsky and Morris, 2000). Value chains are conceptual frameworks used to map and categorise chosen economic, social and environmental processes in service and product value chains, ultimately aiming to help create a better understanding of how and where enterprises and organisations are positioned within the value chain and identifying opportunities and potential leverage points for improvement (Sterman, 2000; Van Den Berg et al., 2013). Product and service value chains are geared towards linear processes and private goods that form part of a conventional neoclassical market setup. Hence, the notion of incorporating public goods (such as ESs) that generally do not have defined market values nor are traded in formal markets, into a value chain analysis will require an alternative approach to conventional linear techniques (Henderson *et al.*, 2002).

The complex and dynamic nature of socio-ecological systems make system behaviour as a function of human and natural disturbances difficult to predict, nevertheless, there have been substantial improvements in the understanding of these systems (EC, 2013). Incorporating ESs thinking into value chain assessments is a relatively recent consideration, thus the literature is scarce (Van Den Berg *et al.*, 2013). Many ESs have been indirectly addressed through approaches to increase the sustainability of value chains, these include certification schemes, corporate social responsibility, risk management and mitigation initiatives (Grigg *et al*., 2009; Weiss *et al.*, 2011). There have been numerous multi-actor activities addressing how biodiversity is and can be integrated into value chains (Bolwig *et al.*, 2010; Van Den Berg *et al.*, 2013). Some of these include the IUCN Global Business and Biodiversity Program (BBP) (Bishop *et al*., 2008), the EU Business and Biodiversity platform, the UNDP protecting biodiversity in working with agribusiness project (Leibel, 2012) and the Business and Biodiversity Offsets Program (BBOP) (Van Den Berg *et al.*, 2013). These initiatives and research endeavours emphasise the limits of market-based approaches for value chains, which range from unorganised and powerless workers and the lack of true market values for ESs to difficulties in product and service commercialisation (Van Den Berg *et al.,* 2013; Wood, 2001). Thus, the development of a framework to analyse the underlying processes adding value to final ESs would contribute towards integrating regulating and supporting services into formal markets.

3. Causal Loop Diagrams

System dynamics is a branch of systems thinking theory often used to explain intricate ecosystem structure and function and illustrate the outcomes of potential management strategies by graphically representing system feedback structures (Kirkwood, 2013; Richardson and Pugh, 1989). CLDs, influence diagrams or cognitive maps are a qualitative diagramming language aimed at graphically illustrating feedback-driven systems (Schaffernicht, 2010; Sterman, 2000). The next stage involves defining stocks and flows of the system and quantifying the interactions between elements to incorporate associated time delays (Ford, 1999).

A typical CLD comprises of a group of symbols representing a particular dynamic system's causal structure. This includes all relevant variables, causal links with a polarity (either negative or positive) and symbols which identify feedback loops and their polarity (Fernald *et al.,* 2012). Each causal link has a direction and a polarity, delay marks are often included to provide an idea of a particular variable's behaviour over time (Ford, 1999; Schaffernicht, 2010). Each arrow is labelled with either a + or a – sign which represents the cause-and-effect relationship between the two variables. A + sign is used to represent a relationship where the two variables change in the same direction while a – sign indicates that the variables change in opposite directions (Kirkwood, 2013; Sterman, 2000).

Conceptualising a complex ecological system not only requires a clear definition of the key elements of the system and the cause and effect relationships between these elements, but also an account of the relationship of the system with other systems. The challenge to communicate the functionality of such a system lies within explaining the relationships between key elements of the system in a simple and transparent way. CLDs facilitate a common understanding and improved insight among stakeholders *vis-à-vis* how the system works and why it responds to external stimuli the way it does (Evans, 2004; Richardson, 1997). Such insight is immensely powerful for developing and strategising ecosystem management practices because it makes critical elements, which are within the stakeholder's control, explicit.

Advancing CLDs to represent natural systems addresses the challenge of building support and consensus for management strategies focussing on the trade-offs between environmental conservation and socio-economic benefits (Evans, 2004). These challenges are derived mainly from difficulty in communicating the value of ESs and the complexity of the underlying ecosystems to a broad audience consisting of different technical backgrounds and potentially conflicting perspectives (Costanza and Ruth, 1998; Lane, 2008; Morecroft, 1982). Such support requires improved insight into the value of ESs through an improved understanding of the workings of the ecosystem itself, which is the primary outcome of the ESVCA framework.

4. Methods

4.1. Ecosystem Services Value Chain Analysis (ESVCA) Framework

Our ESVCA framework constitutes the five iterative process steps illustrated in Figure 1. The method is separated into two distinct phases, the 'CLD development' phase (1-3) and the 'CLD analysis' phase (4-5). Further iterations of the analysis phase are possible once the problem and/or objective has been reconceptualised in light of a prior analysis.

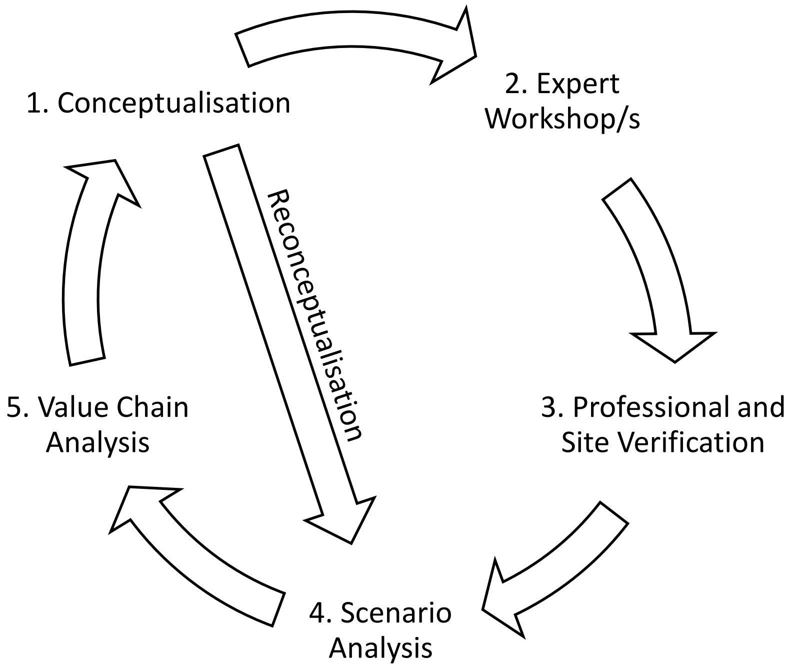

Figure 1: ESVCA framework process cycle.

Table 2 illustrates how each step of the above mentioned processes are included in the two-phased approach. This two-phased approach is based on an adaption and amalgamation of the major system dynamics analysis processes (A1-6) suggested by Ford (1999), the general three-step modelling process (B1-3) outlined by Costanza and Ruth (1998) and the practical value chain analysis steps (C1-3) put forward by Mindtools (2014).

Table 2: Process steps comprised in the ESVCA framework.

ESVCA Framework Process Steps	**A: Major system dynamics analysis steps** **(Ford, 1999)**	**B: Three-step modelling process** **(Costanza and Ruth, 1998)**	**C: Value chain analysis steps** **(Mindtools, 2014)**
1. Conceptualisation	1. Problem definition and delimiting		
2. Expert Workshop	2. Describing the underlying system 3. Model development	1. Low resolution, high generality scoping model	1. Activity Analysis
3. Professional and Site Verification	4. Model Verification	2. Improve on level of detail & create site-specific scenarios	
4. Scenario Analysis	5. Modelling for analysis 6. Communication	3. Analyse scenario and management options	2. Value Analysis 3. Evaluation and Planning
5. Value Chain Analysis			

4.2. Scoping Application

A qualitative scoping application of the ESVCA framework applied to a case study for flood attenuation in the Baviaanskloof catchment, South Africa, is presented here. The aim of the application is to investigate the efficacy of the framework and highlight strengths and weaknesses of the approach for future use.

4.2.1. Study Area

The Baviaanskloof catchment is situated in Eastern Cape Province of South Africa (Figure 2). Several different user groups such as irrigated agriculture, livestock and game farming, conservation and recreation/tourism compete for ESs at different scales (Illgner and Haigh, 2003; Nel *et al.*, 2006). Approximately 65% of the land area in the Baviaanskloof is a nature area and conservancy, ~~The~~ the Baviaanskloof Mega Reserve, used for watershed and biodiversity management, while the rest of the land is used for agriculture, game farming, settlement and tourism (Boshoff, 2005; Knight, 2012). Farm sizes vary significantly and most agricultural land is used for livestock farming, primarily goats and sheep. Relative to this, a small portion of the land is used for irrigated agriculture, the majority of the farms that require irrigation rely on natural springs, boreholes and small farm dams (Boshoff, 2008).

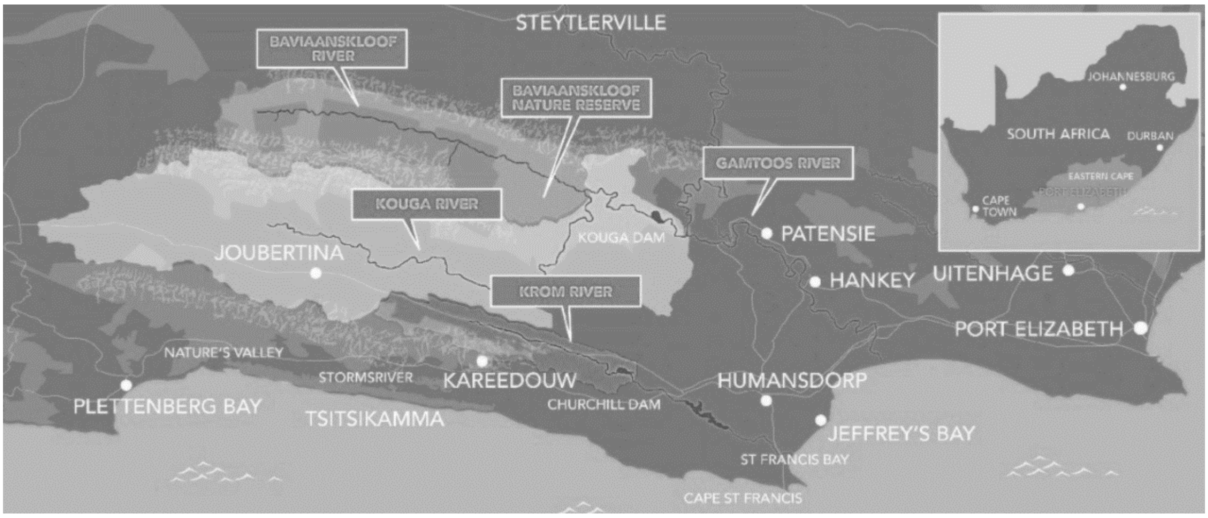

Figure 2: Greater Port Elizabeth Catchment Area (Adapted from Fourreturns, 2014).

The Baviaanskloof catchment is characterised by a highly variable climate and hydrological regime. The catchment is situated in a bimodal rainfall zone with spring and autumn maxima, with an annual average of approximately 350 mm and a large interannual variability (ranging from less than 100 mm to greater than 700 mm) (Mander *et al.*, 2010). Rainfall is primarily convective and/or orographic in nature with more than two thirds falling in the summer months (Jansen, 2008). The mean annual precipitation is characteristically 20% of the mean annual evaporation, resulting in arid conditions through most of the catchment (Van Luijk *et al.*, 2013). Floods pose a significant threat to economic and social activities in the catchment as well as downstream areas (Van Der Burg, 2008). Climate change and land-use models suggest extreme events such as flooding will occur more frequently in the future (Jansen, 2008).

Fire is a common occurrence in the Baviaanskloof and plays an important role in veld management in the area (Boshoff, 2005). The area is governed by a natural fire regime, which is an essential part of many ecological cycles and assists with the propagation of many endemic *Fynbos* species that occur in the area (Booysen and Tainton, 1984). The use of restoration as a management tool to improve flood attenuation capacity, ecosystem health and water provision has grown rapidly over the last decade (Palmer *et al.*, 2014). Catchment restoration includes the building of weirs, gabions and small dams as well as the restoration of alluvial fans and the planting of *Portulacaria afra* (‘spekboom’) in degraded areas (Illgner and Haigh, 2003; Powell, 2009). The ultimate purpose of these activities is to promote diffuse flow of water throughout the catchment in order to retain as much water as possible.

The Baviaanskloof River is a perennial river with a number of non-perennial tributaries that flow down the valley into the river, many of which are canalised to prevent flooding on cultivated land (Jansen, 2008). The Baviaanskloof is a priority biodiversity conservation area for rivers and part of the Kougaberg Strategic Water Source Area, these are areas that supply a disproportionate amount of mean annual runoff to a geographical region of interest (Nel *et al.*, 2013).

4.2.2. Conceptualisation

The first process step involved conceptualising and delimiting the nature of the problem and management challenge to be addressed (step A1). Flooding was identified as a significant threat to the livelihoods of people living in the basin and downstream that is directly affected by natural and anthropogenic processes. Multiple stakeholders including insurance providers, conservationists, researchers and farmers expressed interest in graphically modelling the contribution of underlying processes to the system’s ability to attenuate flooding. Delimiting the scope of the problem involved defining the physical extent of the study area, relevant stakeholders and the particular final ES of interest (i.e. flood attenuation).

4.2.3. Expert Workshops

The second step encompassed hosting multiple expert workshops with participants from academic and professional backgrounds in aquatic science, geomorphology, environmental modelling, ecological economics and hydrology. The specific objectives achieved from the workshops included:

i. Identify and describe final ESs that occur in the study area

ii. Identify and describe associated intermediate ESs

iii. Develop CLD

The problem definition relating to the objective of the study was presented in the beginning of the workshop. The primary aim is to build dialog and facilitate a participatory approach towards developing CLDs with emphasis being placed on an agreed understanding of the interactions between the different final ESs and associated intermediate services (Jafari *et al.*, 2008; Koca and Sverdrup, 2012). Collaborative engagement of experts has been proven to successfully facilitate the determination of the feasibility of different environmental risk management scenarios (Ginsburg *et al.*, 2010).

The workshops focused on producing adequately detailed CLDs that minimise uncertainty yet maintain sufficient levels of complexity, the ‘point of minimum uncertainty’ (Loucks *et al.* 2005). While concurrently limiting it to only the most relevant and impactful variables affecting the final ESs so that it can be easily understood, analysed and then communicated to a range of stakeholders and decision-makers.

Addressing the first workshop objective involved participants conducting ‘blind’ identification of no less than three final ESs. The rigorous, four-rule methodology for distinguishing between final and intermediate ESs developed by Johnston and Russell (2011) was then presented and adopted to ensure a sound understanding of the differentiation between the two concepts. This understanding builds on the logic that interlinked biophysical processes and structures are connected to human well-being by a sequence of intermediate functions and processes, as illustrated by Potschin and Haines-Young (2011) as the ‘ES cascade’. Next cooperative identification of final ESs that occur in the study area are identified in line with the Common International Classification of Ecosystem Services (CICES; EEA, 2017).

The workshop followed a demand side (‘reverse engineering’) approach towards the development of the CLD, beginning with the final ESs and working backwards through the various intermediate services towards the processes and functions that contribute towards the supply of the final ESs. Participants systematically identified a particular beneficiary group, then specific benefits that contribute to the welfare of the beneficiary group and, lastly, the final ES that provides this benefit (e.g. flood attenuation). Flood attenuation was identified as the primary final ES, however, water provision and aquatic ecosystem health were included as final ESs to ensure adequate complexity and coverage of related processes and functions. Building on Landers and Nahlik (2013) and Landuyt *et al.* (2014) the selection of the final ESs for the CLD was based on the relevance of the services to the problem statement, their level of integration into formal markets, whether the quality and/or quantity of delivery can be altered by potential management scenarios and related information/knowledge availability.

The second objective was to identify, categorise and describe the associated intermediate processes, variables, conditions or ESs that directly or indirectly affect the previously identified final ESs. A minimum of one intermediate ES was identified for each of the final ESs identified during the first workshop objective. These were deemed first tier intermediate services as they directly affect the final ESs. Once consensus was established around these intermediate services then additional tiers of intermediate services were identified. All intermediate ESs were distinguished into either environmental or anthropogenic CLD variables. An environmental variable is any process or variable that occurs without or is independent of any direct human influence (e.g. rainfall) and an anthropogenic variable is a process or variable that occurs as a direct result of or is dependent on human agency (e.g. water abstraction). Identifying and describing the necessary intermediate and final ESs completes steps A2 and C1.

System dynamics modelling software (Vensim PLE version 6.3) was used to graphically generate the diagram and display all of the linkages in real time during the workshop. The previously identified final and intermediate ESs were added to the CLD. Then the complex causal relationships and linkages between these ESs were systematically identified and defined, while continuously making note of any factors that may affect the quantity, quality, timing and location of the affected service as per Brauman *et al.* (2007). Ultimately, addressing steps A3 and B1.

4.2.4. Professional and site verification

In completing steps A4 and B2, formal meetings and interviews were set up with professionals and relevant specialists in the study area to scrutinise the CLD. An open dialogue was propagated around the realism and accuracy of the diagram to facilitate the relevant knowledge input into the diagram in terms of specifically defining each variable, relationships between services and units of measurement. Considering the absence of mathematically defined relationships between the interconnected variables, the general flow logic of the CLD was tested and the individual variables and components examined. Relevant disturbances, shocks or changes to the system (i.e. scenarios) were discussed and investigated to verify the robustness of the diagram and identify relevant scenarios for analysis to make it as suitable for the purpose of the research as possible (Grösser, 2012).

4.2.5. Scenario analyses

Scenario analyses are a common approach for analysing trade-offs between ES delivery and their implications for human well-being, most notably in the Millennium Ecosystem Assessment (MA, 2005). Concordantly, they are often an integral component of ES frameworks for management and decision-making (Guswa *et al.*, 2014; Pirard *et al.*, 2010). A particular system change or disturbance is identified and then the resultant impacts throughout the system are methodically analysed to further scrutinise the accuracy of the model and address the problem statement. Each scenario either simulates a potential opportunity or challenge that directly or indirectly affects the provision of a particular final ES.

Firstly, an accurate and detailed description of each scenario was provided. Each analysis was conducted using a supply side approach, beginning with the disturbance to the system then logically following the impact of the disturbance through the various linkages until the nature of the impact on the final ES could be determined. The outcome of the analyses are CLDs illustrating the effect of the disturbance on the system through highlighted causal linkages (arrows), only the direct and indirect impacts of the particular scenario are included. The immediate, short and long-term impacts were distinguished by different colour arrows in an attempt to compensate for CLD’s limited ability to illustrate differences in temporal scales. Specifically, ‘short-term’ refers to impacts that occur within days or weeks of the disturbance while ‘medium/long-term’ considers months to years in duration. It is important to note that it is not possible for one variable to have a shorter term impact on another variable than the original impact on itself. This is coherent with the purpose of the scenario assessments, to illustrate the impact of selected scenarios on the system as a whole, effectively addressing step B3.

4.2.6. Ecosystem service value chain analysis

A structured, demand-side approach starting from the disturbance through to the final impact was used to conduct the value chain analysis. From the scenario analysis CLDs, relevant linear causal pathways (value chains) that impact flood attenuation could be identified. Examining these individual value chains facilitated the identification of the ideal areas (i.e. leverage variables) to intervene to best reduce (increase) the negative (positive) impact of the system change on the final ES. Potential leverage points in these value chains can be single or multiple environmental and/or anthropogenic variables and/or any of the linkages between them. In the case of qualitatively defined causal relationships, no robust conclusions can be drawn as to the impact on the final ES when there are multiple causal pathways affecting the same variable in opposite directions. However, informed deductions can be made about the time scale of the impact and potentially the magnitude of different impacts if the ecosystem processes and dynamics are well understood.

The identification of individual value chain examples allow for linear visualisation and evaluation of how changes to the system affect the provision of final ESs. Using these examples, potential management options were explored for each of the scenarios to provide future planning opportunities to improve the positive impacts or mitigate the negative impacts on the provision of the final services, thus providing information to assist in the determination of the most effective solution to the stated problem. The scenario analysis and ES value chain analysis processes are iterative in nature and can be alternated between to provide as much detail as needed. If the outcome of the analyses still do not provide sufficient information to make a decision around the stated objective, the problem or objective can be reconceptualised to account for the complexity of the system and/or limitations of the model (Figure 1). The combination of these processes involve implementing steps A5, C2 and C3. Step A6 (communication) is completed by writing and publishing the information regarding the application of the ESVCA framework and making it available to all relevant stakeholders and decision-makers.

5. Results

Figure 3 illustrates a CLD representing the complex array of intermediate aquatic ESs in the Baviaanskloof catchment and how these affect the provision of three final ESs in a multi-dimensional snapshot. Each causal linkage (arrow) qualitatively indicates the relationship between the two variables that it connects. Due to the complex and stochastic nature of the system under study and the tiered structure of the intermediate ESs, no positive or negative feedback loops were identified. Kirkwood (2013) and Sterman (2000) identify this type of approach as open loop thinking or ‘pejorative thinking’. Two scenarios were identified that would impact flood attenuation, fire is seen as a threat to the flood attenuation capacity of the system while catchment restoration can improve flood attenuation capacity. The subsequent ES value chain analysis provides insight into several linear causal pathways that impact flood attenuation positively or negatively and evaluate where in the value chain management interventions would best be suited.

5.1. Fire Scenario

The fire scenario is an example of a short-term event that simulates a once off fire event in the Baviaanskloof catchment. This simulation replicates a fire severe enough to significantly reduce the amount of natural vegetation in the area without affecting crops or livestock. While simultaneously not being hot enough to have any type of effect on the soil properties that support the vegetation and associated soil processes. Hence, the only variable that was directly affected through the fire scenario in the CLD was natural vegetation.

Analysing this event as a scenario illustrates the various ripple effects that transpire from this episode over three aforementioned time scales (immediate, short-term and medium/long-term) as exemplified in Figure 4. The CLD demonstrates how the disturbance variable, fire in this case, will have an impact on all three of the final aquatic ESs. It is clear that the fire would decrease the ability of the system to attenuate floods immediately afterwards. However, this outcome does not take into consideration any knock-on effects such as the regrowth of vegetation over time, which could counter these negative impacts.

5.2. Catchment Restoration

The catchment restoration scenario is a demonstration of some of the restoration activities that are currently being performed in the Baviaanskloof catchment. Considering all of these restoration activities broadly, the scenario simulates the impact of increasing the surface roughness within the catchment and the associated impacts throughout the system. Figure 5 illustrates how catchment restoration activities can have a mixed impact on the provision of the three final aquatic ESs as an indirect result of increasing catchment roughness. The system's ability to attenuate floods will be explicitly increased in the immediate term through a decrease in flow velocity and an increase in floodplain capacity.

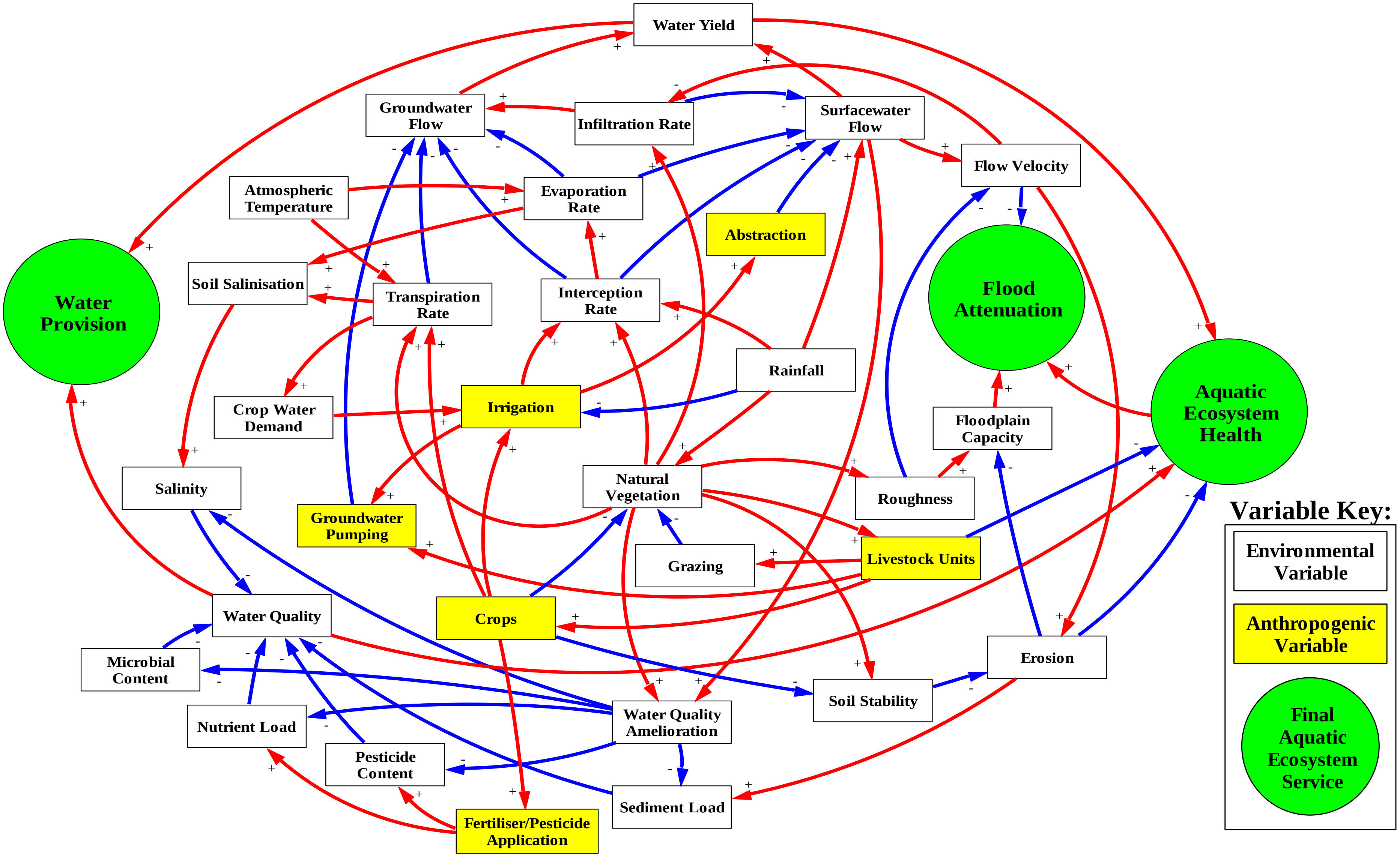

Figure 3: Baviaanskloof Catchment Aquatic Ecosystem Services Causal Loop Diagram.

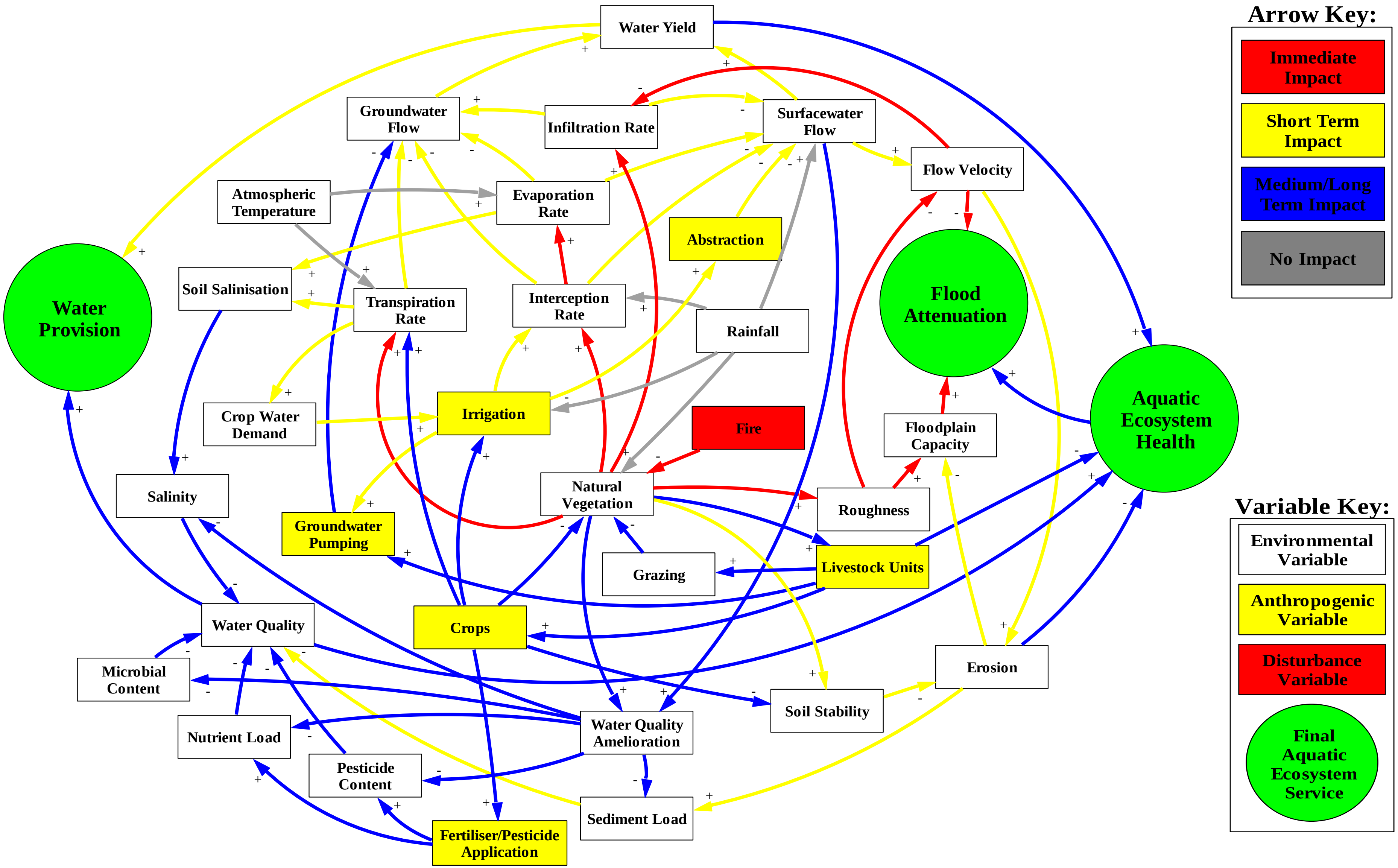

Figure 4: Fire Scenario Analysis Causal Loop Diagram.

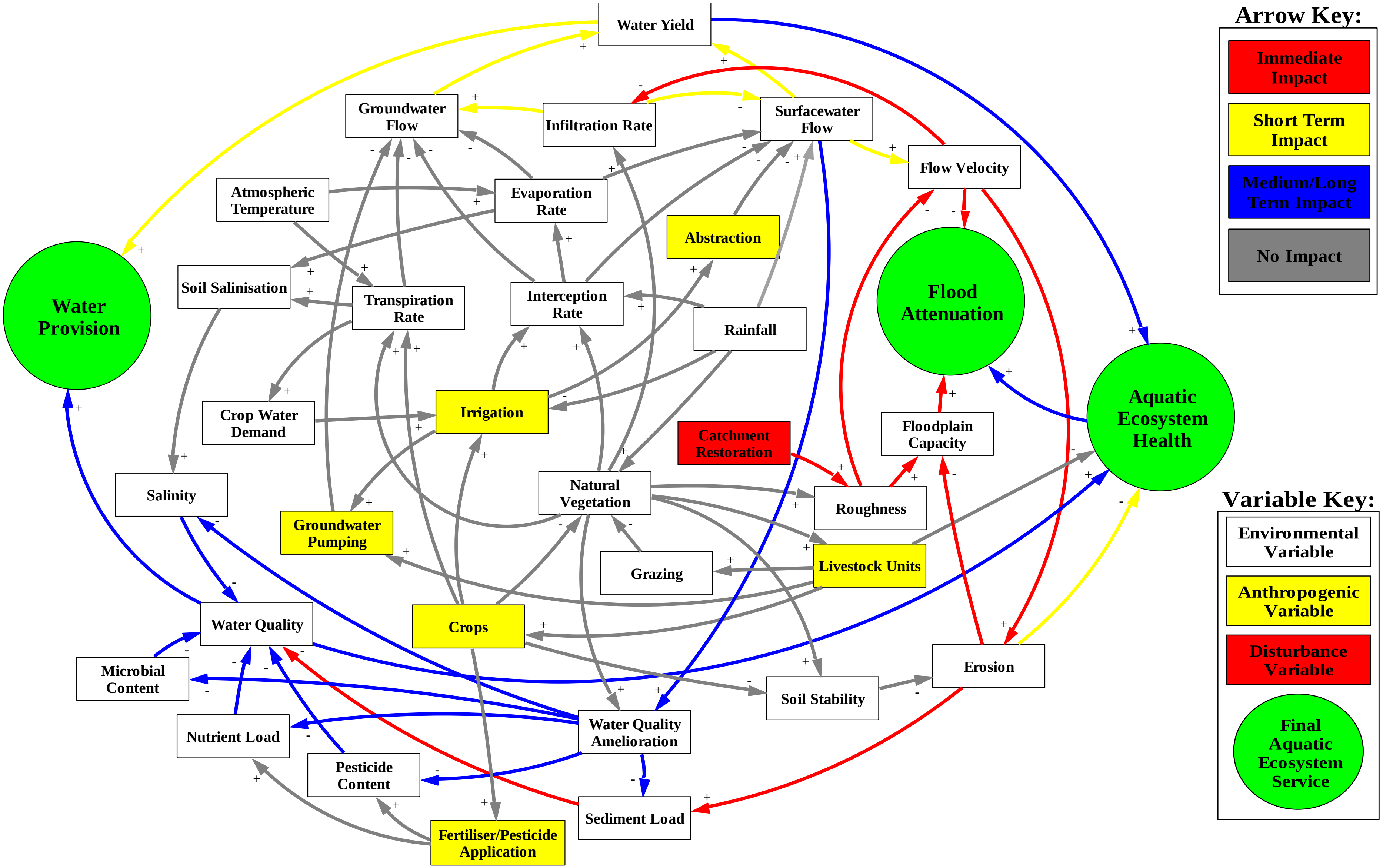

Figure 5: Catchment Restoration Scenario Analysis Causal Loop Diagram.

5.3. Flood Attenuation Value Chain Analysis

The scenario analyses illustrated above outline some of the complex interactions within the system that arise from naturally and anthropogenically induced changes. The outcomes of these analyses are complex in themselves and not straightforward enough for management and decision-making purposes.

Figure 6 demonstrates three examples of linear causal pathways showing the effect of fire and catchment restoration on the system's ability to attenuate floods. The loss of natural vegetation because of a fire event indirectly decreases the floodplain capacity and increases flow velocity; both of which have a negative impact on flood attenuation. Thus, the apparent leverage variables for intervention would be natural vegetation, roughness and infiltration rate. Propagating and promoting the growth of fire resistant indigenous plants would theoretically reduce the loss of vegetation resulting from fire and increase system roughness and the infiltration rate (Booysen and Tainton, 1984). This could be supplemented with a geological survey that identifies the most efficient and effective areas to promote infiltration (e.g. closest to the phreatic or saturated zone). Alternatively, the aforementioned catchment restoration scenario, directly and over a relatively fast time scale, improves the flood attenuation capacity in the Baviaanskloof catchment.

Identifying relevant leverage variables that are required for the provision of a particular final ES can provide crucial information for private and public decision makers. For example, insurance companies interested in the provision of flood attenuation could utilise this approach to identify possible intervention measures that will reduce the impact of fire on the ability of the system to attenuate floods. Fire provides a potential financial threat to an institution of this nature by reducing the ability of the system to attenuate flooding, as a result more flood damage claims are put forward. Thus, if a cost-effective option to reduce the effect that fire has on the ability of the system to attenuate flooding can be identified, this will increase the profitability of the company in the long run.

If these specific relationships between fire and flood attenuation highlighted in Figure 6 are quantified, then it would be possible for the firm to conduct a benefit-cost analysis to determine whether the investment would be financially viable or not. Aside from other apparent benefits such as improved water retention in the system, which will benefit local residents etc. This method could also be adopted to develop disaster management plans by government with the aim of preventing the loss of life and infrastructural damage.

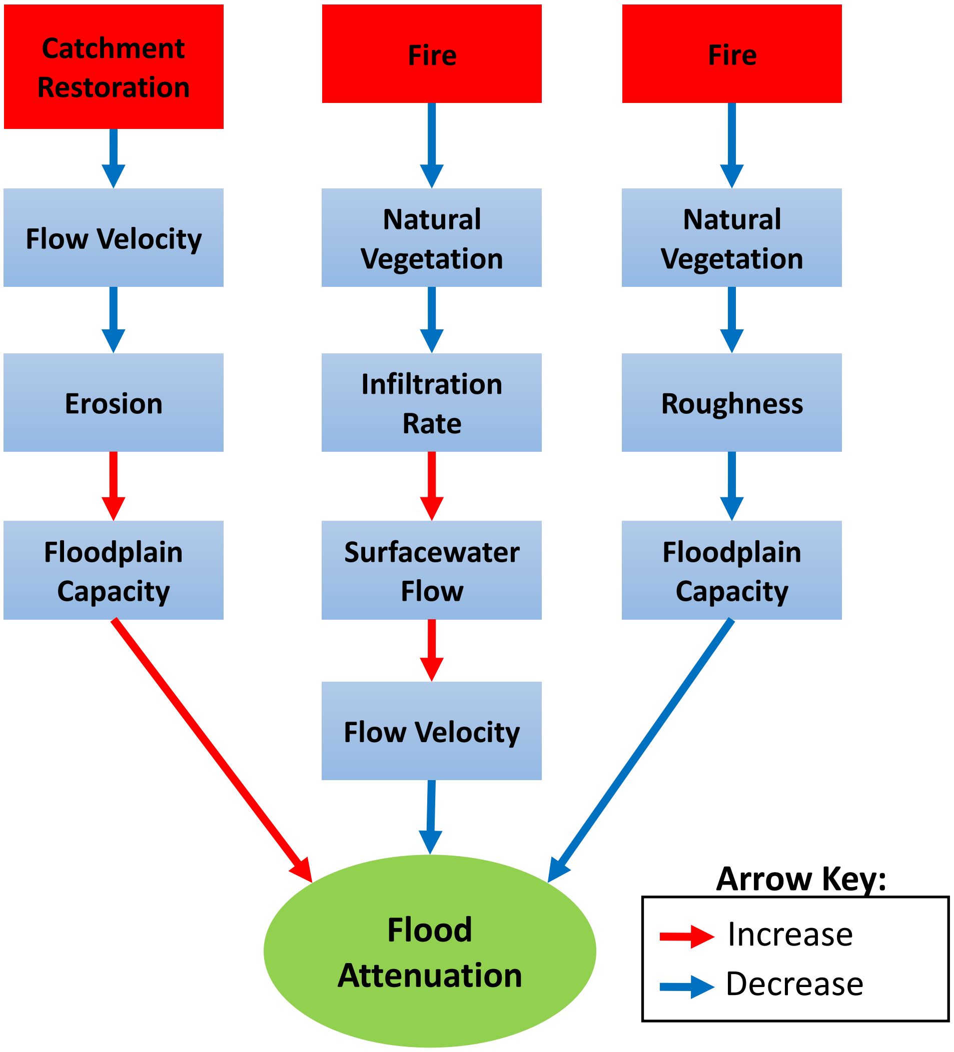

Figure 6: Linear Causal Pathways Impacting Flood Attenuation.

6. Discussion and Conclusion

In light of the existing and predicted consequences of ecosystem degradation and the recent increase in scientific research surrounding ES delivery, modern society is undergoing a seminal change in the way benefits of natural ecosystems are understood and valued (Maltby and Acreman, 2011). There is global consensus amongst scientists and economists alike that the natural systems providing the necessary services that support and drive modern day society have entered a period of drastic change (Carpenter *et al.*, 2009; De Groot *et al.*, 2010b; COWI, 2014; Griggs *et al.*, 2013; MA, 2005; ONEMA, 2011; O'Neill *et al.*, 2010; Ostrom, 2009; Rockström *et al.*, 2009; Wallace, 2008). The concept of ESs is an extension of both ecological functioning and economic externalities that creates a nexus between the fields of ecology and economics, despite their conflicting ideologies (Fisher *et al.*, 2009; Gómez-Baggethun and Barton, 2012).

The ESVCA framework presented here attempts to narrow the gap between traditional, linear economic thought and the complex dynamic systems they attempt to model and/or value. The tool is more inclusive than current environmental management models, as it includes environmental and anthropogenic components in a flexible manner to accommodate system complexity. The model outputs are predictive in nature, allowing pro-active strategies to be implemented through the identification of potential future system threats via relevant scenario analyses. The decision-making tools generated from the ESVCA framework promote systemic thinking within management endeavours, a need widely acknowledged across disciplines (Sterman, 2000).

The ESVCA framework has the potential to incentivise private and public investment into the sustainable management of ecosystems by visually demonstrating the various system processes that contribute to the generation of marketed and non-marketed goods and services. This will not only assist with the integration of ESs into formal markets but could result in numerous additional benefits associated with healthy ecosystem functioning. Trade-off analysis between various ESs is facilitated through this model as individual inputs and their potential to add value are compared and scrutinised (Brauman *et al.,* 2007). The method has the ability to address the issues of changing ecological feedbacks, however, currently cannot account for potential regime shifts (Carpenter *et al.*, 2009).

The primary limitation associated with a tool of this nature is its inability to accurately account for changes in spatial scales because it has to be calibrated to a specific area. Due to the complex, stochastic and dynamic nature of socio-ecological systems it is difficult to delimit the optimal size of a CLD that minimises model uncertainty while maintaining sufficient complexity to realistically represent the system (Loucks *et al*. 2005). Without empirically defining the causal relationships between the different variables, it is not possible to determine the magnitude of impacts. Hence, when there are two conflicting impacts on one variable, one cannot categorically deduce the direction of the causality. Similarly, each relationship between different variables in the system had to be classified exclusively as either positive or negative. This approach cannot capture the impacts of differing magnitudes of change if they result in a change in the causality of the relationship. For example, a small increase in one variable could have a positive impact on the next variable, but a large increase in that same variable could result in a negative impact on the next variable.

The scenario analyses were limited to analysing one scenario at a time. This is a result of numerous conflicting impacts on the same variable occurring when too many influences are included at the same time. As the relationships between the different variables are not quantified, one cannot deduce the outcome of conflicting impacts on one variable over time. Thus, associated knock-on impacts cannot be simultaneously analysed without quantified relationships representing system behaviour over time. For example, knowledge of an impending fire might change human behaviour in terms of land use, which may affect the magnitude of the outcome of flooding on the system.

Future research directions lie in the incorporation of the ESVCA approach into multiple framework modelling and decision-making procedures, such as integrated environmental assessments (Toth and Hiznyik, 1998). Combining complex models alongside multiple decision frameworks will provide the best opportunity to generate credible, legitimate and salient information (Cash *et al.,* 2003) that can be utilised as efficiently and effectively as possible. Practical assessment of decision problems involving many decision makers and system variables generally use Pareto-optimal solution sets (Lund and Palmer, 1997), the ESVCA framework can contribute towards multi-criteria decision analyses to generate optimal solutions. Quantifying the magnitude of the relationships between various intermediate and final ESs will facilitate deeper analysis of ES value chains and the associated system impacts of interventions. However, the data limitations and associated system complexity will limit the potential of this approach for large scale analysis. However, qualitative analyses such as the one developed in this paper could address this issue

The ESVCA framework enables the identification of forward linkages and ripple effects in individual value chains of final ESs and the identification and assessment of challenges and opportunities in the value chains of final ESs and associated markets. Ultimately, facilitating the development of strategies and recommendations to improve the efficiency and effectiveness of final ES provision. This approach provides the framework through which progress towards understanding and integrating fully inclusive value chain analyses, which incorporate environmental processes and services, into policy and decision-making is a realistic outcome. Continued development of the ESVCA framework presented in this paper will contribute towards the advancement of a standardised ESVCA framework and improve the quantity and quality of ES-based information available to decision-makers.

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References

BALETA, H. and PEGRAM, G. 2014. *Water as an input in the food value chain: Understanding the food energy water nexus*. WWF-SA, South Africa.

BISHOP, J., KAPILA, S., HICKS, F., MITCHELL, P. and VORHIES, F. 2008. *Building Biodiversity Business*. Shell International Limited and the International Union for Conservation of Nature, London, UK.

BOLWIG, S., PONTE, S., DU TOIT, A., RIISGAARD, L. and HALBERG, N. 2010. Integrating poverty and environmental concerns into value-chain analysis: a conceptual framework. *Development Policy Review,* 28(2):173-194.

BOOYSEN, P.D. and TAINTON, N.M. 1984. Ecological effects of fire in South African ecosystems. *Ecological Studies,* 48:1-18.

BOSHOFF, A.F. 2008. *The Baviaanskloof Mega-Reserve: from concept to implementation*. African Centre for Conservation Ecology Report: 58, Nelson Mandela Metropolitan University, Port Elizabeth, South Africa.

BOSHOFF, A.F. 2005. *The Baviaansklooof Mega-reserve: An environmentally, socially and economically sustainable conservation and development initiative*. Terrestrial Ecology Research Unit Report: 52, Nelson Mandela Metropolitan University, Port Elizabeth, South Africa.

BOYD, J. and BANZHAF, S. 2007. What are ecosystem services? The need for standardized environmental accounting units. *Ecological Economics,* 63:616-626.

BRAUMAN, K.A., DAILY, G.C., DUARTE, T.K. and MOONEY, H.A. 2007. The nature and value of ecosystem services: an overview highlighting hydrologic services. *Annual Review of Environment and Resources,* 32:6.1-6.32.

CARPENTER, S.R., MOONEY, H.A., AGARD, J., CAPISTRANO, D., DEFRIES, R.S., DIAZ, S., DIETZ, T., DURAIAPPAH, A.K., OTENG-YEBOAH, A., PEREIRA, H.M., PERRINGS, C., REID, W.V., SARUKHAN, J., SCHOLES, R.J. and WHYTE, A. 2009. Science for managing ecosystem services: beyond the Millennium Ecosystem Assessment. *PNAS,* 106(5):1305-1312.

CASH, D. W., CLARK, W. C., ALCOCK, F., DICKSON, N. M., ECKLEY, N., GUSTON, D. H., JAGER, J. and MITCHELL, R. B. 2003. Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences*, 100(14):8086-8091.

COSTANZA, R. 2008. Ecosystem services: Multiple classification systems are needed. *Biological Conservation*, 141:350-352.

COSTANZA, R. and RUTH, M. 1998. Using dynamic modelling to scope environmental problems and build consensus. *Environmental Management*, 22(2):183-195.

COWI. 2014. *Support policy development for integration of ecosystem services assessments into WFD and FD implementation*. Annex Report. [Online]. Available: https://circabc.europa.eu/sd/a/79584b30a2a34fa89d0785303dfdf9b1/ Ecosystem%20services_WFD_FD _Annex%20report_Final.pdf. [01/06/2015].

DE GROOT, R.S., FISHER, B., CHRISTIE, M., ARONSON, J., BRAAT, L., GOWDY, J., HAINES-YOUNG, R., MALTBY, E., NEUVILLE, A., POLASKY, S., PORTELA, R. and RING, I. 2010a. *Integrating the ecological and economic dimensions in biodiversity and ecosystem service valuation*. In: Kumar, P. (ed). The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations. Earthscan, London, UK.

DE GROOT, R.S., ALKEMADE, R., BRAAT, L., HEIN, L. and WILLEMEN, L. 2010b. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecological Complexity*, 7:260-272.

EC (European Commission). 2013. *System of Environmental-Economic Accounting.* European Commission, Organisation for Economic Co-operation and Development, United Nations, World Bank [Online]. Available: http://unstats.un.org/unsd/ envaccounting/eea_white_cover.pdf. [29/05/2015].

EEA (European Environment Agency). 2015. *CICES: Towards a common classification of ecosystem services.* European Environment Agency. [Online]. Available: http://cices.eu/. [01/06/2016].

EVANS, D. 2004. *A comparative valuation of ecosystem services: Lents project case study.* Prepared for city of Portland watershed management program, ECONorthwest.

FISHER, B., TURNER, R.K. and MORLING, P. 2009. Defining and classifying ecosystem services for decision making. *Ecological Economics*, 68:643-653.

FERNALD, A., TIDWELL, V., RIVERA, J., RODRIGUEZ, S., GULDAN, S., STEELE, C., OCHOA, C., HURD, B., ORTIZ, M., BOYKIN, K. and CIBILS, A. 2012. Modeling sustainability of water, environment, livelihood, and culture in traditional irrigation communities and their linked watersheds. *Sustainability*, 4:2998-3022.

FORD, A. 1999. *Modeling the Environment: An Introduction to System Dynamics Modeling of Environmental Systems*. Island Press, Washington, US.

FOURRETURNS. 2014. *The FourReturns Development Company*. Available: http://www.fourreturns.co.za/. [05/09/2016].

GINSBURG, A.E., CRAFFORD, J.G. and HARRIS, K.R. 2010. *Framework and Manual for the evaluation of aquatic ecosystems services for the Resource Directed Measures.* Water Research Commission Report: TT 462/10, Pretoria, South Africa.

GÓMEZ-BAGGETHUN, E., DE GROOT, R., LOMAS, P.L. and MONTES, C. 2010. The history of ecosystem services in economic theory and practice: from early notions to markets and payment schemes. *Ecological Economics,* 69: 1209-1218.

GÓMEZ-BAGGETHUN, E. and BARTON, D.N. 2012. Classifying and valuing ecosystem services for urban planning. *Ecological Economics,* 86: 235-245.

GRIGGS, D., STAFFORD-SMITH, M., OWEN, G., ROCKSTRÖM, J., ÖHMAN, M.C., SHYAMSUNDAR, P., STEFFEN, W., GLASER, G., KANIE, N. and NOBLE, I. 2013. Sustainable development goals for people and planet. *Nature*, 495:305-307.

GRÖSSER, S.N. 2012. *Co-evolution of standards in innovation systems: the dynamics of voluntary and legal building codes*. Springer Science and Business Media, Heidelberg, Germany.

GUSWA, A.J., BRAUMAN, K.A., BROWN, C., HAMEL, P., KEELER, B.L. and SAYRE, S. 2014. Ecosystem services: challenges and opportunities for hydrologic modelling to support decision making. *Water Resources Research*, 50:4535-4544.

HANLEY, N., SHOGREN, J.F. and WHITE, B. 2007. *Environmental economics in theory and practice*. Palgrave Macmillan, Beijing, China.

HENDERSON, J., DICKEN, P., HESS, M., COE, N. and YEUNG, H.W. 2002. Global production networks and the analysis of economic development. *Review of International Political Economy,* 9(3):436-464.

ILLGNER, P.M. AND HAIGH, E.H.2003. *Identification, mapping and present state assessment of the wetlands in the Baviaanskloof River Catchment*. Report for Working for Wetlands. Eastern Cape IWR Wetland Group. Institute for Water Research, Rhodes University, Grahamstown, South Africa.

JAFARI, M., AMIRI, R.H. and BOUROUNI, A. 2008. *An interpretive approach to drawing causal loop diagrams*. Proceedings of the 26th International Conference of the System Dynamics Society, July 2008, Athens, Greece.

JANSEN, H.C. 2008. *Water for food and ecosystems in the Baviaanskloof Mega Reserve: land and water resources assessment in the Baviaanskloof, Eastern Cape Province, South Africa*. Alterra Report: 1812, Wageningen University, Wageningen, Netherlands.

JOHNSTON, R.J. and RUSSELL, M. 2011. An operational structure for clarity in ecosystem service values. *Ecological Economics*, 70:2243-2249.

KAPLINSKY, R. and MORRIS, M. 2000. *Handbook for value chain research*. Prepared for the International Development Research Centre. [Online]. Available: https://www.ids.ac.uk/ids/global/pdfs/VchNov01.pdf. [17/10/2016].

KIRKWOOD, C.W. 2013. *Chapter 1: System behaviour and causal loop diagrams*. Arizona State University, Arizona, US. [Online]. Available: http://www.public.asu.edu/~kirkwood/sysdyn/SDIntro/ch-1.pdf. [05/05/2016].

KNIGHT, F.H. 2012. *Agricultural assessment of the Baviaanskloof*. Report prepared for Greenchoice. Agri Informatics Development Trust, Durbanville, South Africa.

KOCA, D. and SVERDRUP, H. 2012. *Use of causal loop diagrams and systems analysis to explore alternative climate change adaption strategies in Seyhan River Basin, Turkey*. Proceedings of the 30th International Conference of the System Dynamics Society, July 2012, Gallen, Switzerland.

LANDERS, D.H. AND NAHLIK, A.M. 2013. *Final Ecosystem Goods and Services Classification System (FEGS-CS)*. Environmental Protection Agency Report: EPA/600/R-13/ORD-004914, Washington, USA.

LANDUYT, D., LEMMENS, P., D'HONDT, R., BROEKX, S., LIEKENS, I., DE BIE, T., DECLERCK, S.A.J., DE MEESTER, L. and GOETHALS, P.L.M. 2014. An ecosystem service approach to support integrated pond management: a case study using Bayesian belief networks – highlighting opportunities and risks. *Environmental Management*, 145:79-87.

LANE, D.C. 2008. The Emergence and use of diagramming in system dynamics: a critical account. *Systems Research and Behavioral Science*, 25:3-23.

LEIBEL, N. 2012. *Protecting biodiversity in production landscapes: a guide to working with agribusiness supply chains towards conserving biodiversity*. United Nations Development Programme, New York, US.

LIMBURG, K.E., O'NEILL, R.V., COSTANZA, R. and FARBER, S. 2002. Complex systems and valuation. *Ecological Economics*, 41:409-420.

LOEHE, C. 2004. Challenges of ecological complexity. *Ecological Complexity*, 1:3–6.

LOUCKS, D.P., Van Beek, E., Stedinger, J.R., Dijkman, J.P.M. and Villars, M.T. 2005. *Water resources systems planning and management: an introduction to methods, models and applications*. UNESCO, Paris.

LUND, J.R. and PALMER, R.N. 1997. Water resource system modelling for conflict resolution. *Water Resources Update, UCOWR*, 108: 70-82.

MA (Millennium Ecosystem Assessment). 2005. *Ecosystems and human well-being*. Island Press, Washington, DC.

MALTBY, E. and ACREMAN, M. 2011. Ecosystem services of wetlands: pathfinder for a new paradigm. *Hydrological Sciences Journal*, 56(8):1341-1359.

MANDER, M., BLIGNAUT, J., VAN NIEKERK, M.A., COWLING, R., HORAN, M.J.C., KNOESEN, D.M., MILLS, A., POWELL, M. and SCHULZE, R.E. 2010. *Baviaanskloof – Tsitsikamma Payment for ecosystem services: A feasibility assessment*. South African National Biodiversity Institute, Pretoria, South Africa.

MILL, J.S. 1882. *A system of logic, ratiocinative and inductive, being a connected view of the principles of evidence and methods of scientific investigation* (8e). Harper and Brothers, New York, US.

MINDTOOLS. 2014. *Value Chain Analysis: Achieving Excellence in Things that Really Matter*. [Online]. Available: www.mindtools.com/pages/articles/newTMC_10.htm. [12/09/2016].

MORECROFT, J.D.W. 1982. A critical review of diagramming tools for conceptualising feedback system models. *Dynamica*, 8:20–29.

NEL, J., COLVIN, C., LE MAITRE, D., SMITH, J. and HAINES, I. 2013. *South Africa's Strategic Water Source Areas*. Council for Scientific and Industrial Research Report: CSIR/NRE/ECOS/ER/2013/0031/A, Pretoria, South Africa.

NEL, J.L., SMITH-ADAO, L., ROUX, D.J., ADAMS, J., CAMBRAY, J.A., DE MOOR, F.C., KLEYNHANS, C.J., KOTZE, I., MAREE, G., MOOLMAN, J., SCHONEGEVEL, L.Y., SMITH, R.J. and THIRION, C. 2006. *Conservation Planning for River and Estuarine Biodiversity in the Fish-to-Tsitsikamma Water Management Area*. Water Research Commission Report: K5/1486, Pretoria, South Africa.

ONEMA (The National Agency for Water and Aquatic Environments). 2011. *Assessing the ecological services of aquatic environments scientific, political and operational issues*. [Online]. Available: http://www.onema.fr/IMG/EV/publication/ecological-services/ ecological-services-couv.pdf. [12/05/2015].

O'NEILL, D.W., DIETZ, R. and JONES, N. 2010. *Enough is Enough: Ideas for a sustainable economy in a world of finite resources*. The report of the Steady State Economy Conference. Center for the Advancement of the Steady State Economy and Economic Justice for All, Leeds, UK.

OSTROM, E. 2009. A general framework for analysing sustainability of social-ecological systems. *Science*, 325(1):419-422.

PALMER, M.A., FILOSO, S. and FANELLI, R.M. 2014. From ecosystems to ecosystem services: stream restoration as ecological engineering. *Ecological Engineering,* 65:62-70.

PIRARD, R., BILLE, R. and SEMBRES, T. 2010. *Questioning the theory of Payments for Ecosystem Services (PES) in light of emerging experience and plausible developments*. Institute for Sustainable Development and International Relations, Paris, France.

POTSCHIN, M.B. and HAINES-YOUNG, R.H. 2011. Ecosystem services: exploring a geographical perspective. *Progress in Physical Geography,* 35(5):575-594.

POWELL, M.J. 2009. *Restoration of degraded subtropical thickets in the Baviaanskloof Megareserve, South Africa: The role of carbon stocks and Portulacaria afra survivorship*. Unpublished MSc Thesis, Department of Environmental Science, Rhodes University, Grahamstown, South Africa.

RAWORTH, K. 2017. *Doughtnut economics: seven ways to think like a 21st-century economist.* Random House, London, UK.

RICHARDSON, G.P. 1997. Problems in causal loop diagrams revisited. *System Dynamics Review,* 13:247-252.

RICHARDSON, G.P. and Pugh, A.L. 1989. *Introduction to System Dynamics Modeling*. Pegasus Communications, Waltham, US.

ROCKSTRÖM, J., STEFFEN, W., NOONE, K., PERSSON, Å., CHAPIN, F.S., LAMBIN, I.E., LENTON, T.M., SCHEFFER, M., FOLKE, C., SCHELLNHUBER, H., NYKVIST, B., DE WIT, C.A., HUGHES, T., VAN DER LEEUW, S., RODHE, H., SÖRLIN, S., SNYDER, P.K., COSTANZA, R., SVEDIN, U., FALKENMARK, M., KARLBERG, L., CORELL, R.W., FABRY, V.J., HANSEN, J., WALKER, B., LIVERMAN, D., RICHARDSON, K., CRUTZEN, P. and FOLEY, J. 2009. Planetary boundaries: exploring the safe operating space for humanity. *Ecology and Society,* 14(2):32.

SCHAFFERNICHT, M. 2010. Causal loop diagrams between structure and behaviour: A critical analysis of the relationship between polarity, behaviour and events. *Systems Research and Behavioural Science,* 27:653-666.

STERMAN, J. 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. McGraw-Hill, Boston, US.

STERN, N.H. 2007. *The economics of climate change: the Stern review*. Cambridge University Press, Cambridge, UK.

TEEB (The Economics of Ecosystems and Biodiversity). 2010. *The economics of ecosystems and biodiversity: ecological and economic foundations*. Kumar, P. (Ed). Earthscan, London and Washington.

TOTH, F. and HIZNYIK, E. 1998. Integrated environmental assessment methods: evolution and applications. *Environmental Modelling and Assessment,* 3:193-210.

VAN DEN BERG, J., INGRAM V.J., BOGAARDT, M.J. and HARMS, B. 2013. *Integrating ecosystem services into the tropical timber value chain: Dutch policy options from an innovation system approach*. The Statutory Research Tasks Unit for Nature & the Environment WOt-werkdocument: 344, Wageningen, Netherlands.

VAN DER BURG, L. 2008. *Valuing the benefits of restoring the water regulation services, in the subtropical thicket biome: a case study in the Baviaanskloof-Gamtoos watershed, South-Africa.* Unpublished MSc Thesis, Wageningen University, Wageningen, Netherlands.

VAN LUIJK, G., COWLING, R.M., RIKSEN, M.J.P.M. and GLENDAY, J. 2013. Hydrological implications of desertification: degradation of South African semi-arid subtropical thicket. *Journal of Arid Environments,* 91:14-21.

VIHERVAARA, P., RÖNKÄ, M. and WALLS, M. 2010. Trends in Ecosystem Service Research: Early Steps and Current Drivers. *Ambio,* 39:314–324

WALLACE, K.J. 2008. Classification of ecosystem services: Problems and solutions. *Biological Conservation,* 139:235–246.

WEISS, G., PETTENELLA, D., OLLONQVIST, P. and SLEE, B. 2011. *Innovation in Forestry Territorial and Value Chain Relationships*. CABI, Wallingford, UK.

WOOD, A. 2001. Value chains: An economist's perspective. *IDS Bulletin,* 32(3):1-5.