Science of the Total Environment 559 (2016) 326–338

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Evaluating sustainable adaptation strategies for vulnerable mega-deltas using system dynamics modelling: Rice agriculture in the Mekong Delta's An Giang Province, Vietnam

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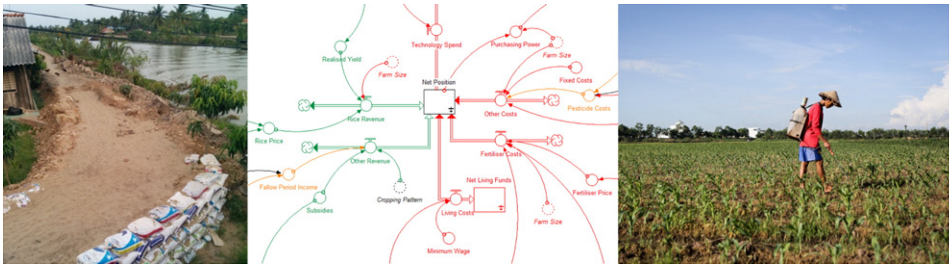
HIGHLIGHTS

- Mekong delta adaptation strategies are evaluated with system dynamics modelling.
- For the first time, sediment deposition is integrated into the socioeconomic system.
- The shift towards high dykes and triple-cropping benefits land-wealthy farmers.
- Mechanisms shown through which triple-cropping forces debt on poorer farmers.
- Advantages of strategic facilitation of sediment deposition are shown.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 8 January 2016
Received in revised form 22 February 2016
Accepted 23 February 2016
Available online 12 April 2016

Editor: D. Barcelo

Keywords:
Adaptation
Sediment
System dynamics
Rice
Mekong Delta

ABSTRACT

Challenging dynamics are unfolding in social-ecological systems around the globe as society attempts to mitigate and adapt to climate change while sustaining rapid local development. The IPCC's 5th assessment suggests these changing systems are susceptible to unforeseen and dangerous ‘emergent risks’. An archetypal example is the Vietnamese Mekong Delta (VMD) where the river dyke network has been heightened and extended over the last decade with the dual objectives of (1) adapting the delta's 18 million inhabitants and their livelihoods to increasingly intense river-flooding, and (2) developing rice production through a shift from double to triple-cropping. Negative impacts have been associated with this shift, particularly in relation to its exclusion of fluvial sediment deposition from the floodplain. A deficit in our understanding of the dynamics of the rice-sediment system, which involve unintuitive delays, feedbacks, and tipping points, is addressed here, using a system dynamics (SD) approach to inform sustainable adaptation strategies. Specifically, we develop and test a new SD model which simulates the dynamics between the farmers' economic system and their rice agriculture operations, and uniquely, integrates the role of fluvial sediment deposition within their dyke compartment.

We use the model to explore a range of alternative rice cultivation strategies. Our results suggest that the current dominant strategy (triple-cropping) is only optimal for wealthier groups within society and over the short-term (ca. 10 years post-implementation). The model suggests that the policy of opening sluice gates and leaving paddies fallow during high-flood years, in order to encourage natural sediment deposition and the nutrient replenishment it supplies, is both a more equitable and a more sustainable policy. But, even with this approach, diminished supplies of sediment-bound nutrients and the consequent need to compensate with artificial fertilisers will mean that smaller-scale farmers in the VMD are more vulnerable to accruing debt.

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http://dx.doi.org/10.1016/j.scitotenv.2016.02.162

1. Introduction

Many of the world's deltas, which have a combined population of over 500 million people (14% of the global total), are threatened with major flooding and land loss as a consequence of rising relative sea-levels (Syvitski et al., 2009). The displacement of people, the resultant loss of lives and livelihoods, and declining food security are some of the potential impacts of the 'drowning' of the world's subsiding deltas and these adverse impacts are significant enough to have both regional and global ramifications (Kuenzer and Renaud, 2012; Warner, 2010). Our understanding of the physical processes driving accelerated relative sea-level rise (RSLR) in these vulnerable deltas is increasing. The net rate of RSLR is now known to be controlled by the interplay between processes that contribute to RSLR, namely: natural subsidence due to the delta's compaction under its own weight; accelerated subsidence due to anthropogenic influences (e.g. groundwater and/or hydrocarbon extraction); eustatic sea-level change; and those processes which can slow or reverse RSLR, most notably aggradation as a result of the deposition of sediment supplied to the delta plain (Syvitski and Kettner, 2011). The unbalancing of these processes in deltas around the globe, frequently in favour of processes that enhance RSLR, is driving exposure vulnerability, a problem which is often exacerbated by the presence of significant local (social) sensitivity (Szabo et al., 2015; Tessler et al., 2015).

With large areas of vulnerable deltas at risk, hard and soft adaptations are urgently required to mitigate the threat of RSLR. However, in many deltas, particularly those located in developing nations, a policy response is also required to tackle (and adapt to) other development-linked drivers of change, which include issues such as urbanisation, agricultural intensification, and population growth (Kuenzer and Renaud, 2012). Coping with the threats posed by these dual drivers of change (environmental change and economic development), termed 'double exposure' (O'Brien and Leichenko, 2000), requires systemic understanding of the interacting social, economic, and physical components of the world's delta systems.

In highly complex social-ecological systems, such as river deltas, adaptations aiming to manage double exposure often involve trade-offs, and some negative impacts may be unavoidable (Suckall et al., 2014). Previous work has identified two particular risks in the adaptation process; actions may either have 'maladaptive traits' themselves (Barnett and O'Neill, 2010), or they may create undesirable impacts when they interact with other development or climate change oriented actions, creating a phenomenon termed 'emergent risk' in the IPCC's 5th assessment report (Oppenheimer et al., 2014).

With the above risks in mind, adaptation to double exposure in the world's deltas is receiving growing attention. For example, Smajgl et al. (2015); Temmerman and Kirwan (2015), and Tessler et al. (2015) have all recently emphasised the risks associated with what they argue are the 'short term' hard-engineering solutions that are being pursued at present. For example, the use of river dyke networks to protect agriculture and infrastructure from inundation has become common place (e.g. Hung et al., 2014; Hood, 2004; Nixon, 2003; Seto et al., 2002; Hensel et al., 1998; Ibáñez et al., 1997). These dyke networks may provide valuable protection from local flooding in the near term but, through their concurrent exclusion of fluvial sediment deposition (Manh et al., 2014) and hence their adverse impact on RSLR, they can threaten the long-term sustainability of the delta-body (Syvitski et al., 2009). Specifically, sediment deposition that is excluded by the presence of dykes could otherwise mitigate exposure to flood and inundation risks by offsetting land surface elevation reductions due to subsidence. However, an important but lesser discussed way in which sediment deposition can additionally benefit local social systems is through the deposition of attached nutrients which subsequently help maintain the productivity of ecosystems and agriculture (Olde Venterink et al., 2006).

As a result of the potential negative impacts associated with hard-engineering interventions, alternative 'nature-based' solutions that involve the strategic facilitation of floodplain sediment deposition to build land height and counter RSLR are increasingly being advocated as an alternative management approach. This concept of facilitated sediment deposition, which emerged in the more developed Mississippi and Ebro Deltas (Rovira and Ibáñez, 2007; Day et al., 2005), has now been recognised more widely as a potential adaptation strategy (Ibáñez et al., 2014) and is being incorporated into the management plans of developing deltas including large, highly vulnerable, deltas such as the Mekong, through the "Mekong Delta Plan" (MDP, 2013). However, such 'nature-based' adaptation strategies have not yet been systemically evaluated against the hard-engineering, dyke-based, alternatives. For example, from the perspective of some stakeholders, such 'nature-based' strategies may conflict with other local non-adaptation oriented objectives, such as achieving maximum short-term agricultural production and/or flood protection.

While our understanding of the physical processes involved in floodplain sediment dynamics and their interaction with hydraulic infrastructure has been developing in recent years (e.g. Manh et al., 2014; Hung et al., 2014), complementary knowledge of the socioeconomic trade-offs linking them to agriculture remains lacking. This knowledge deficit broadly includes the value and role of the free fertilising nutrients bound to the fluvial sediments deposited in deltas, and the optimal socioeconomic balance between flood exclusion and facilitation. In many deltas, decisions on floodplain sediment management are intrinsically linked to agricultural development objectives and management decisions that affect the livelihoods of many millions of farmers. In the Asian mega-deltas in particular, comparatively poor farmers have become dependent for their subsistence on the stable environment provided by hydraulic infrastructure, and the high productivity of soils, creating a phenomenon that Evers and Benedikter (2009) have termed a 'modern hydraulic society'. Recent research has highlighted the important role that wealth inequalities can play in determining how well deltaic societies cope with environmental change (Szabo et al., 2015). As a result, adaptation planning must be conducted with systematic consideration of the potential impacts of different implementation strategies and paying particular attention to the factors which determine a strategy's winners and losers.

To address some of these issues, in this paper we examine socioeconomic dynamics linking local livelihoods, hydraulic infrastructure, management practices, fluvial inundation, and sediment deposition in the Mekong delta. The Mekong delta (introduced further in Section 3) is currently facing a major sustainability challenge (Anthony et al., 2015). As the world's third largest delta (Coleman and Huh, 2003) it hosts a population of nearly 20 million, but its significance for the present study lies primarily in its pivotal importance to the food security of the Southeast Asia region more generally. Specifically, the delta provides 50% of Vietnam's food (GSO, 2014) and over 90% of Vietnam's rice production (Kontgis et al., 2015). Not only does rice production form the foundation of the local economy (as discussed in Section 3) but, as Mohanty et al. (2013) outline, rice is the staple food product of hundreds of millions of the world's poorest people. Globally, there are significant threats to rice production as it is primarily concentrated in a small number of low-lying and/or flood-prone areas (e.g. deltas), making rice production particularly vulnerable to the impacts of environmental change (Wassmann et al., 2009). Our focus on the Mekong may therefore have relevance to the world's other major rice producing deltas.

To investigate the trade-offs involved in adaptation and agricultural development management decisions we evaluate the competing merits of different policy scenarios by developing, testing and applying a novel system dynamics model (SDM). The new SDM is, to our knowledge, the first that is capable of integrating the role of deltaic sediment-bound nutrient deposition into the economic and decision making systems of Mekong delta rice farmers. We employ the SDM to evaluate the system dynamics, such as thresholds, feedbacks, and delays, of the recent transition (adaptation) from the prior low dyke network to sediment-excluding high dykes, and especially the shift from the double to triple rice-cropping production system which has resulted (Kontgis et al., 2015). As the first such study, our work has relevance to a range of delta environments where there are urgent needs for evaluations of different adaptation policies, but particularly contexts where sediment exclusion due to investment in hydraulic infrastructure may be affecting rice cultivation. Within the specific context of the Mekong delta, our work has policy relevance as our lack of understanding of the socioeconomic role of sediment in the double to triple-cropping switch has been identified in the Mekong Delta Plan (2013, p.24), a key national policy analysis document, as a specific knowledge gap.

2. Aims and objectives

In this paper we aim to perform a comparative evaluation of a suite of adaptation strategies for the agricultural sector of the Vietnamese Mekong delta (as represented by the exemplar of rice cultivation in An Giang province). Specifically, we apply a system dynamics methodology to explore the dynamics of different courses of action implemented in a context of double exposure to environmental change and development pressures. The following specific objectives are addressed:

- To identify the key changes in socioeconomic system dynamics resulting from the shift (adaptation) from low to high river dykes, and the associated exclusion of fluvial sediment to rice paddies.
- To determine the effectiveness of alternative rice production policies which have been implemented and proposed.
- To evaluate how the different policies analysed operate and perform across farmers within different wealth strata.

3. Study area

The VMD (Fig. 1A) is a highly productive agricultural region that has been undergoing rapid economic development since the 'Doi Moi' opening of the Vietnamese markets in 1986. In large part the VMD's development has been driven by increases in rice production and export (ISG-MARD, 2011). Expansion and intensification have been facilitated by improvements in farming practice, uptake of modern rice varieties, increased input levels, and multiplication of crops (Garschagen et al., 2012). However, the technological development of agriculture in the region remains relatively low and the largest single cost in the rice production process remains artificial fertilisation, constituting around 40–50% of overall expenditure (Pham, 2010, p.230). Despite the region's rapid development, poverty is still prevalent and farmers face multiple challenges, such as declining productivity, income insecurity, and debt (Garschagen et al., 2012; Swain et al., 2008). As of 2012, the General Statistics Office of Vietnam (GSO, 2014) estimated that the poverty rate in the VMD was 16.2%. Poverty in this context was defined by an individual income threshold (at 2012 prices) of less than approximately US$500 per year (Demombynes and Linh, 2015).

As discussed above, the Mekong delta is one of the world's largest rice producing regions, with much of the crop being exported. As such the Mekong delta is strategically important in terms of both the Vietnamese economy and global food security (Smajgl et al., 2015). An Giang province (Fig. 1B), located in the northern part of the Vietnamese delta, has been selected as the focus of this study as it can be considered typical of those parts of the delta where rice production is the dominant economic activity, with 85% of land use devoted to rice (AGSO, 2013). The intensification of rice production in the delta (Kontgis et al., 2015) has required ever increasing control of the fluvial floods which would otherwise inundate the majority of the northern part of the delta. Typically, rice production takes place within rectangular dyke rings (Fig. 1B) which protect multiple smallholder rice paddies

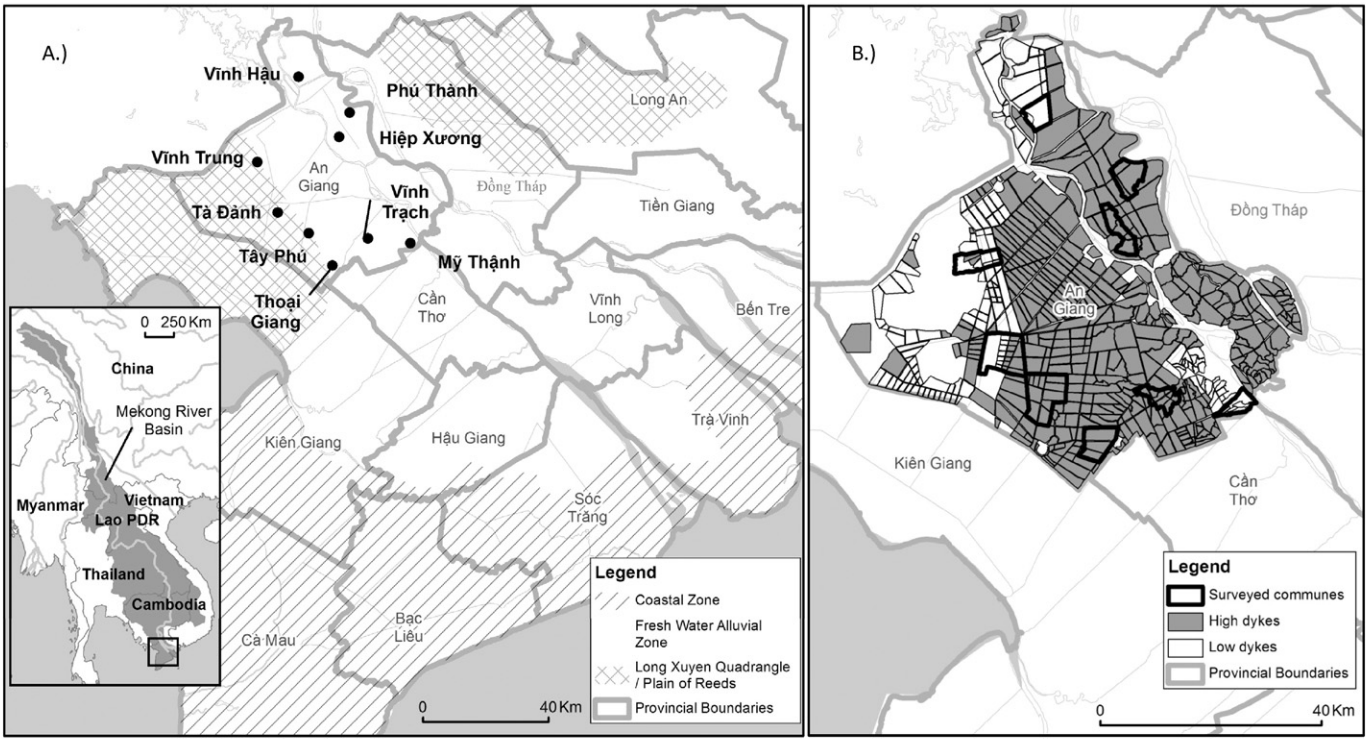

Fig. 1. A.) The provinces and agro-ecological zones of the Vietnamese Mekong Delta. Highlighted are the names of the nine surveyed communes and inset is the Mekong river basin which supplies the sediment entering the delta from the north. B.) An Giang province and the high dyke network which represents the adaptation action undertaken. The boundaries of the nine surveyed communes are also indicated. Data on the location and extent of the dyke network as of 2007 was provided by the WISDOM project (2014). The WISDOM project dyke height estimates were updated using agricultural data contained within the An Giang Statistical Yearbook (AGSO, 2013) to estimate their 2013 extent.

from the annual monsoonal flood and supply irrigation water year-round. However, these ring dyke networks also dramatically affect the inundation regime. Fluvial floods are now subject to a second key driver of change, climate change. Of the multiple climate-change risks present in the VMD, increases in the frequency and intensity of fluvial and coastal flooding stand-out as particular threats to the wellbeing of the delta's inhabitants and those dependent on its economy (Van et al., 2012). The structures (dykes and sluice gates) previously built to control fluvial flooding for the safety of residents and crops have now been adopted as important components of the government's strategy for adapting to climate change (Vietnamese Government, 2011; MARD, 2008; MPI, 2006). An Giang province is representative of much of the rest of the Vietnamese Mekong delta in having undergone a large programme of dyke height increases from low (0–2 m) to high (3.5 m+) since the new millennium.

However, a growing body of evidence associates ring dyke networks with both positive and negative impacts on local communities and the wider delta (Birkmann et al., 2012; Garschagen et al., 2012; Pham, 2011; Sakamoto et al., 2009). On the one hand, high dykes help meet both development and adaptation objectives by facilitating triple-cropping and protecting livelihoods against intensifying fluvial flooding and inundation driven by sea-level rise; on the other, the exclusion of sediment (and associated nutrients) reduces agricultural productivity in the long term, and accelerates the rate of RSLR. The result is a nexus of conflicting long and short-term development and adaptation objectives and pressures which create an archetypal example of a system with potential for emergent risk.

3.1. Rice cultivation systems in the Mekong delta

At present, two primary farming systems operate within An Giang's dyke rings, double and triple rice-cropping, which are split approximately 1:2 by area (Kontgis et al., 2015), inclusive of one variant on triple-cropping, the 3-3-2 cycle (introduced below). The double-cropping pattern is almost always found within low (0–2 m) dyke rings and was the dominant practice during the 1990s. In such dyke rings flooding can still take place when peak water heights overflow the dykes during the monsoon season. During these periods of flooding suspended sediment may be deposited on the floodplain (Hung et al., 2014); the quality and quantity of the deposited sediments varying spatially and inter-annually (Manh et al., 2014). Aware that the sediment deposits have many of the nutrients required for rice agriculture (estimated at 50% of the total N, P, and K required for a crop; Manh et al., 2014) double-cropping farmers have adopted the practice of spreading the deposited sediment evenly over their paddy. Moreover, farmers also factor the quantity of sediment they perceive as having been deposited into a wider decision making process regarding the quantity of artificial fertiliser they apply in a given year. This decision making process is based on a combination of local and historical knowledge, crude tools for measuring crop-health, and the farmer's allocative efficiency (i.e. the farmer's assessment of the optimal choice based on current prices and yields). Farmers may apply a certain quantity of fertiliser, but the total quantity of nutrients reaching the plant is then subject to their technical efficiency and the technology at their disposal (Khai and Yabe, 2011). Once a rice crop has been harvested the majority is sold for export, though a small quantity may be kept back for personal consumption. Traditionally, farmers employing the double-cropping system will also seek income from secondary sources, such as fishing or small-scale livestock husbandry. This is because, under double-cropping, farmers have approximately a four month period (Jul–Oct) during the monsoon season when their paddy is left fallow and they can focus on non-rice income generation.

Within the area enclosed by high (2 m+) dyke rings, an area which almost doubled between 2000 and 2010 (Kontgis et al., 2015), flooding either does not take place at all or comes via sluice gate operation, reducing the ‘natural’ (i.e. pre-high dyke) rate of sediment deposition (Hung et al., 2014). The exclusion of the annual flood also reduces local fishing potential and, perceiving a fallow compartment and subject to government production targets, farmers are incentivised to grow a third rice crop – potentially increasing annual yield per hectare by a factor of 1.5. The additional crop results in a considerably increased workload and hence reduces the triple-cropping farmer's capacity to generate income from other sources (Garschagen et al., 2012). Furthermore, the loss of the flushing effect of the monsoonal flood is cited as a factor contributing to proportionally higher pest and disease costs (Pham, 2011). Aware of some of these negative impacts, the An Giang provincial government recommend adoption of a variant 3-3-2 cropping cycle, in which the paddy is left fallow and a full flooding season is facilitated by sluice gate operation every third year. However, this recommended strategy has thus far seen low uptake (Sakamoto et al., 2009) and was found in only 2 of 9 An Giang communes in a 2014 survey conducted by Chapman et al. (2016).

4. Model construction

In environmental systems, such as the VMD, which are subject to high levels of forecasting uncertainty and which are heavily influenced by local management decisions a ‘predict-then-act’ (Lempert et al., 2004) approach to adaptation decision making can be problematic. Uncertainty and complexity can mean that identifying a single preferential adaptation strategy can be challenging and furthermore, can enhance the desirability of short-term, ‘palliative’, solutions (Füssel, 2007). As a result, interest has grown in ‘robust’ decision making (Lempert et al., 2006). For robust decision making knowledge is required about the operational sources of vulnerability within a social-ecological system, at which action can be targeted (Costa et al., 2011; Fraser et al., 2011). System dynamics modelling (SDM) enables complex interactions between system components to be evaluated through exploration of how stocks (i.e. accumulation points, such as the stock of nutrients held within the floodplain) and flows (also called rates, as represented by the differential equations which define how the level of a stock varies over time) connect to form a system. SDMs are not usually regarded as forecasting tools, but rather as tools that enable users to investigate system dynamics, identify unforeseen outcomes and compare scenarios of action or system change (Ford, 2010, p. 59–60; Simonovic and Li, 2004). These three strengths have begun to see the SDM methodology being applied to the task of climate change mitigation and adaptation policy evaluation (e.g. Dace et al., 2015; Gies et al., 2014) and, more generally, to evaluating sustainable policy in coupled hydrological and economic systems (e.g. Alcalá et al., 2015; Sušnik et al., 2013).

In the following sub-sections we outline how our SDM was constructed and tested for the Mekong delta, focusing on the (i) identification of system processes, (ii) representation of stocks and flows, (iii) evaluation of the model, and (iv) the formulation of the specific policy scenarios evaluated herein.

4.1. Identification of system processes

Scoping field studies were performed in 2013 and 2014 during which semi-structured interviews were conducted with six local academics, four senior provincial policy makers, and eighteen commune authority leaders to identify expert and stakeholder views on key aspects of system behaviour within the VMD rice producing regions. The knowledge gained was used to build a causal loop diagram (CLD) of the system in question (Fig. 2). Fig. 2 highlights how interactions between three key sectors of the system (physical, economic, and decision making) are analysed. Fig. 2 also presents the core feedback loops which were identified through the process of stakeholder engagement and included in the model, as well as one example of a feedback loop that was regarded as lying outside the boundaries of the system under

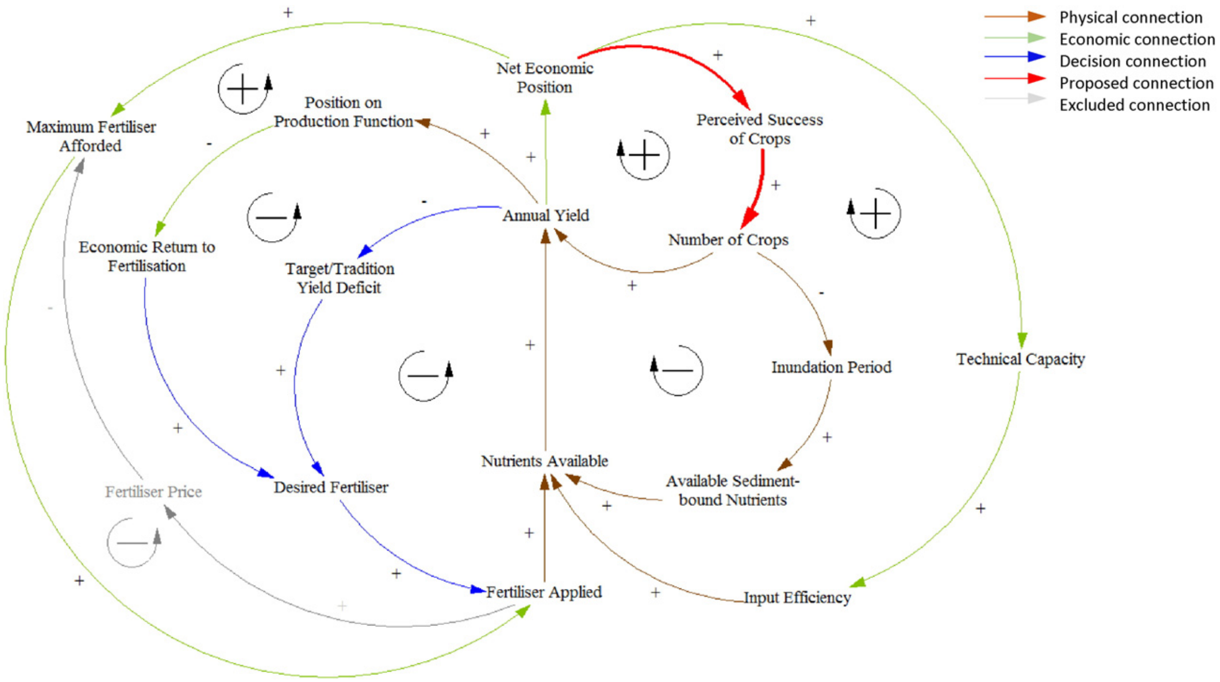

Fig. 2. A casual loop diagram (CLD) showing modelled connections, their nature, individual polarity (positive or negative), and the overall loop polarity (sometimes termed the momentum of the loop, which can either be reinforcing '+' or balancing '—'). Included is one example of a feedback loop excluded from the model, with this exception, this diagram represents the boundaries of the model.

examination and therefore excluded from the model. Key exogenous forcing variables that were included in the model were: increases and unpredictability in fertiliser and rice prices, increases in rice yield due to new variety development, unpredictability in rice yield due to weather variability, change and variability in the quantity of sediment-bound nutrients deposited annually by fluvial inundation, and increases and unpredictability in the costs associated with pests and disease (particularly those associated with the triple-cropping production regime).

4.2. Stock and flow design

The model's stock and flow structure was designed and parameters calibrated utilising a combination of the knowledge gained in key-informant interviews and through a comprehensive literature search. Each of the forcing variables listed above were assigned a rate of change and variability (standard deviation) the values of which were extracted from secondary data sources (listed and described in Table 1) using

Table 1
The (exogenous) model driving data and the values for each which were used to initiate the model, their sources, information type, and an assessment of the source's reliability. 'Overall score' represents the aggregated source reliability score based on the system set out in the Supplementary Materials. Highlighted, are the components which were taken forward for sensitivity analysis.

Data	Source (s)	Information Type	Units	Initial value	Overall score
Inter–annual variability of suspended sediment concentration	SIWRR, 2013 (daily time series 2005–2011); Shreshtha et al. 2013 (predictions)	Statistical/ Modelled	Fraction (standard deviation)	0.2	89%
Dam trapping efficiencies (end of simulation sediment reduction)	Kummu et al. 2010; Kondolf et al. 2014	Modelled	Fraction	0.84	69%
Total nutrient contentof suspended sediment (N, P, K)	Manh et al. 2014	Uncontrolled	Kg/ha/yr	300	78%
Variability of rice prices	FAO, 2014 (monthly time series 2008–2014), Survey data	Statistical	Fraction (standard deviation)	0.05	78%
Rate of change of rice prices	FAO, 2014 (monthly time series 2008–2014)	Statistical	%/ha/yr/yr	1	78%
Variability of fertiliser prices	World Bank, 2014 (monthly time series 2000–2014), Survey data	Statistical	Fraction (standard deviation)	0.1	78%
Rate of change of fertiliser prices	World Bank, 2014 (monthly time series 2000–2014)	Statistical	%/ha/yr/yr	1.05	33%
Growth rate of rice yields due to rice variety development	Laborte et al. 2012; Ray et al. 2012; Tran and Kajisa, 2006	Statistical/Case study	%/ha/yr/yr	1.01	89%
Non–rice income achievable	Bosma et al. 2005	Statistical	'000 VND/yr	4800	78%
Exogenous variability of rice yield	GSO, 2014 (seasonal time series 1995–2013)	Statistical	Fraction (standard deviation)	0.1	78%
Rice price	Survey data	Statistical	'000 VND/Kg	4.5	78%
Fertiliser price	Survey data	Statistical	'000 VND/Kg	6	78%
Minimum wage level	Vietnamese Government, 2013	Law	'000 VND/person/yr	7200	100%

Table 2
Endogenous modelled processes (key micro-systems within the model), their sources, information type, and an assessment of their source's reliability. 'Overall score' represents the aggregated source reliability score based on the system set out in the *supplementary materials*. Highlighted, are the components which were taken forward for sensitivity analysis.

Modelled processes	Source(s)	Information Type	Overall score
Sediment deposition process	Manh et al. 2014; Hung et al. 2014	Uncontrolled	75%
Floodplain nutrient accumulation process	Tsheboeng et al., 2014	Uncontrolled	58%
Nutrient fixing and leaching process	Liang et al., 2013; Phong et al., 2011	Controlled/Uncontrolled	67%
Rice nutrient requirement (production function)	Pham et al. 2004; Witt et al. 1999	Controlled	83%
Technological advancement process	Reardon et al. 2014; Rutten et al., 2014	Statistical/Modelled	58%
Technical efficiency rate	Khai and Yabe, 2011; Hueglas and Templeton, 2010	Statistical	75%
Technological investment return	Tin et al., 2008; Tran et al., 2000	Statistical	75%
Sediment perceived versus fertiliser applied decision process	Survey data	Stakeholder	100%
Fixed cost variation between cropping patterns	Survey data	Stakeholder	83%
Pesticide cost variation between cropping patterns	Survey data	Stakeholder	83%
Fertiliser subsidy policy	Tran, 2014	Expert	67%
Farmer's propensity to invest	Personal Intuition	Personal Intuition	–
Farmer's fraction of funds kept as contingency	Personal Intuition	Personal Intuition	–

simple statistical analysis; their initial values are summarised in Table 1. As is common in SDM projects a variety of different data sources were used to inform the design of the stock and flow structures used to create the model; the processes modelled and their sources are outlined in Table 2. Our model was developed using *ISEE Systems*' IThink SDM software package.

4.3. Evaluation of model performance

As noted above, SDMs are built with the objective of understanding a system to address a problem or answer a question, and not to predict or forecast future conditions (Sterman, 2000). System dynamics models should therefore be evaluated with this purpose in mind. As such, in the following sub-sections we describe three key phases of our model evaluation process, which follows Sterman's (2000) 'Tests for assessment of dynamic models'.

4.3.1. Parameter assessment

In the first phase of the model evaluation process, termed the judgemental parameter assessment, all of the sources informing relationships in the model were assigned a score for their strength in terms of: statistical confidence (where applicable), study location transferability, spatial scale comparability, and quantity of evidence/studies (see Supplementary Information for further details on this evaluation process; Tables 1 and 2 present the average reliability scores of the exogenous data sources and the modelled relationships, respectively). The process of evaluating confidence in data sources identified five key parameters against which there was notably greater uncertainty (scoring one standard deviation below the mean or more): (i) the fertiliser price rate of change (%/season), (ii) the farmers' propensity to invest for the future (% profit/season), (iii) the fraction of the farmers' incomes kept as contingency (% profit/season), (iv) the time from sediment-bound nutrient deposition to availability for plant uptake (seasons), and (v) the rate of depreciation of farming technology investments (%/season). These five parameters were therefore considered further during the model evaluation phase which addressed the model's sensitivity, as described in Section 4.3.3.

4.3.2. Comparison with reference mode

The second phase of evaluation involved undertaking statistical comparisons of SDM derived data versus real-world data (the latter being termed the reference mode by Ford, 2010) obtained from a comprehensive 2014 survey of 195 An Giang rice farming households (Chapman et al., 2016; Fig. 1 shows the locations of the communes within which the survey took place). It should be recognised that these observational data are subject to their own uncertainty, particularly as the survey required farmers to recall information spanning a six year historical period (2008–2013). We compared simulated and observed time-series of the yield/fertiliser ratio achieved by farmers operating three different farming systems: (i) double-cropping, (ii) triple-cropping, and (iii) those farmers who changed cropping system during the observation period. The yield/fertiliser ratio was selected as the primary metric for model comparison because its temporal trends succinctly summarise the status and sustainability of an agricultural system and it is commonly utilised to benchmark the performance of policies implemented in agricultural systems (see Khai and Yabe, 2011).

When simulating the yield/fertiliser ratio time-series under the three key system conditions listed above (i-iii) the model produced relative errors (RE) against the reference mode that varied between 0.1 and 7.3% (Table 3). There is evidence ($p < 0.05$) of a systematic error in all of the comparisons of the absolute values of the yield/fertiliser ratio achieved by farmers of around 1 t/t (5.3–7.3%). When comparing rates of change there is no statistically significant ($p < 0.05$) evidence of a systematic error, the model predicts the correct signal in all three cases, and RE ranges from 0.1–3.9%. The model would appear to provide robust simulations of the two crop system but, overestimates the reported values under the triple-cropping system.

4.3.3. Sensitivity analysis

Sensitivity analyses were conducted on the five parameters identified in Section 4.3.1 as having notably weak evidence bases. In doing so our objective was to investigate the potential for such weaknesses to confound our overall confidence in the model simulations. We used

Table 3
A summary of the results of the statistical tests used to validate the model outputs against the farmer-reported data. SE = systematic error (reported data − modelled data), RE = relative error.

Cropping pattern	Absolute Yielfert values			Rate of change of Yielfert		
	SE (t/t)	SE *p*-value	RE (%)	SE (t/t/yr)	SE *p*-value	RE (%)
Two-crop	0.95 ± 0.58	<0.001	5.3	0.001 ± 0.023	0.999	0.1
During cropping system change	1.14 ± 1.00	0.013	6.3	0.039 ± 0.039	0.058	3.9
Three-crop	−1.36 ± 0.70	<0.001	7.3	0.019 ± 0.028	0.354	1.9

Table 4
A summary of the general sensitivity degrees, GS_Q, between five parameters and four output variables: desired level of fertilisation (DF); rice yield (RY); cash profit (CP); and technical efficiency (TE). Values >0.1 are highlighted in bold.

Parameter	Indicator DF	RY	CP	TE
Fertiliser price rate of change	0.085	0.011	**0.65**	0.048
Farmer's propensity to invest	0.035	0.003	**0.12**	0.034
Farmer's fraction of funds kept as contingency	0.008	0.002	0.001	0.006
Time to nutrient availability	0.015	0.000	0.017	0.003
Technological depreciation rate	0.051	0.008	0.004	0.044

the sensitivity degree (S_Q), a metric commonly applied in SDM contexts and shown in Eq. (1), to measure the sensitivity of four key indicators against incrementally increased levels of variation (±10%) in the five parameters tested. The general sensitivity degree (GS_Q) represents the average of all sensitivity degrees (S_Q) measured for the different levels of perturbation of a particular parameter.

$$S_Q = \left|\frac{\Delta Q_{(t)}}{Q_{(t)}} \cdot \frac{X_{(t)}}{\Delta X_{(t)}}\right| \tag{1}$$

(Zhang et al., 2008)$Q_{(t)}$ = Model output at time t; $X_{(t)}$ = Model input at time t; S_Q = Sensitivity degree.

The majority of the tested combinations revealed low (<0.1) general sensitivity (Table 4). However, a notable exception is that increases in the fertiliser price rate of change were seen to have a considerable influence over the farmer's cash profit (CP). The time-dependence of the sensitivity of this key relationship is explored in Table 5. The sensitivity of cash profit to the fertiliser price rate of change grows throughout the test simulation such that, by the end of the simulation, its influence on CP was proportionately greater than the initial change made to the parameter. Considering the unpredictable nature of the fertiliser market it is unlikely that any greater confidence in this particular parameter is attainable. However, rather than invalidating the model, this finding might be regarded as offering insight into the nature of the system; as such it is investigated further in Section 5.1.

4.4. Scenario design and testing

All simulations conducted herein were initialised with those forcing parameters which change throughout the simulation (e.g. fertiliser price) set below the levels at which policy testing began (equivalent to the 2013 averages — see Supplementary Information) and a ‘spin-up’ simulation period was used to bring the system up to the testing initiation point, i.e. average 2013 levels. The model took a spin-up period of 53 time steps (seasons — of which there are three seasons per calendar year) to reach this policy initiation point. The spin-up was conducted with the model parameters set to simulate the double-cropping rice production system which has historically operated within the study region. At the end of the spin-up period minor adjustments were made to the model's parameters to configure the model for a specific rice-cultivation policy (as detailed in Table 6) and the model was then run over a period of 20 further years (i.e. 60 model time steps/seasons), the testing period. With the number of forcing variables affecting the system and our stated aim not to *forecast* the system's conditions, it was felt that moving any further into the future could potentially render our outputs meaningless, while 60 time steps is sufficiently long for the system dynamics to emerge. The model constructed represents the VMD system as we presently understand it and with a wide variety of parameters making up the model it was important to reduce the risk of issues such as overfitting affecting the predicted data.

Table 5
A breakdown of the sensitivity degrees (S_Q) of the parameter representing fertiliser price increase across various time steps and levels of alteration.

Change in parameter level	Time step 53	73	93	113
−10%	0.064	0.42	0.92	1.7
−20%	0.062	0.47	0.91	1.4
−30%	0.060	0.84	0.72	0.99
−40%	0.059	0.67	0.67	0.91

Table 6
A summary of the policy scenarios tested with the model. Each policy was implemented through manipulation of the parameter “cropping pattern”.

Policy	Description and background
1	Business-as-usual for triple-cropping farmers (two-thirds of AG farmers); at the end of the spin-up farmers switch to and operate the triple-cropping system
2	Business-as-usual for (one-third of AG) farmers who remain operating the old double-cropping system
3	Sluice gates are opened to allow floodplain sediment deposition once every three years (the 3-3-2 system)
4	Sluice gates are opened to allow sediment deposition in years of high flood and sediment deposition potential (a strategy advocated by farmers interviewed). Sediment deposition rates were smoothed over 12 model time steps (4 years) and deposition was allowed only in years exceeding 10% above the smooth.

Four policy scenarios are analysed herein (Table 6, see also Section 3.1). Three of those scenarios simulated rice cropping systems currently operated in the region: (1) the triple-cropping system (business-as-usual); (2) the double-cropping system (the traditional system); and (3) the 3–3-2 cropping rotation that has been implemented in some districts to alleviate a negative impact (sediment exclusion) of the triple-cropping system. Additionally, one further policy not currently operated in the region was tested. This policy (4) is consistent with the recommendations made by the MDP (2013) in which triple-cropping continues but with strategic flooding (and double-cropping) during years of high flood and sediment deposition potential. Notably, policy 4 was also informally described as being preferred by many of the farmers interviewed in the survey undertaken by Chapman et al. (2016). Policy 4's key difference from the 3-3-2 system (policy 3) is its increased flexibility, that is, its responsiveness to high flow events, which maximises sediment deposition and flood protection benefits.

Each policy set-up was tested for three different farm sizes (we use farm size as a proxy for wealth), upper quartile = 3 ha (UQ), median = 1.7 ha, and lower quartile = 1 ha (LQ), based on the survey data collected in An Giang. Each set-up was subjected to Monte-Carlo simulation, with 100 runs, each influenced by stochastic, normally distributed, random variation entering the system through the exogenous forcing variables detailed in Section 4.1 and defined by the standard deviation values derived from secondary data and available in Table 1. This feature gives the model the power to test the system's dynamic response to temporal peaks and troughs in exogenous variables.

4.5. Analysis of model outcomes

The SDM results were initially analysed using a set of key indicators designed to capture differences in dynamics between scenarios; those indicators included: (i) annual rice production per hectare, (ii) government net profit (rice export revenue assuming an export tax rate of 10%, based on Pham, 2010, minus any policy costs), (iii) total annual sediment deposition allowed, (iv) farmer mean disposable income (farming profits minus minimum wage), (v) farmer income stability (mean number of times disposable income dropped to zero per simulation), (vi) farmer debt (mean total at simulation end), and (vii) prevalence of debt among farmers (percentage of farmers in greater than USD 50 debt at simulation end). In all cases individual metrics are standardised (out of 100) using the linear additive model (unweighted) commonly used for multi-criteria decision analysis (MCDA) and scored on a simplified '+/—' scale, as is commonly used in system dynamics projects (e.g. Costa et al. 2011). This scoring system aims to ensure conclusions are not drawn from the model's outputs which are in fact beyond the model's capabilities. However, for reference, and particularly to highlight the model's standard errors which are difficult to represent under this scoring system, all raw results are included in the Supplementary Materials. All results were analysed with a discount rate of 3.5% applied post-hoc, as recommended by the British Government's (2011) Green Book for time periods spanning 30 years or less, as is the case here.

5. Results

5.1. Double vs triple-cropping

We first look at the key changes in socioeconomic system dynamics resulting from the main transition or 'adaptation' that has already taken place, i.e. the shift from low to high river dykes associated with the move from double (policy 2) to triple (policy 1) rice-cropping.

First, and as expected, across all farm sizes Fig. 3 shows that a clear substitution of sediment (and associated nutrients) for annual rice production (and hence government export profit) takes place when the double-cropping spin-up period ends (at season 53, marked by the dashed vertical green line in Fig. 3) and the triple-cropping (policy 1) begins. In Table 7 we compare the system conditions of the farmers (two thirds of An Giang province) who pursued policy 1 (triple-cropping) with the farmers who remained double-cropping (policy 2). Table 7 indicates that the shift to triple-cropping has negative outcomes on the majority of indicators, barring rice production and government profit, for farms of smallest size (LQ). Results for farms of median size are similar, except that triple-cropping (policy 1) affords greater income stability in this case. However, for farmers with greatest land wealth (i.e. the UQ of farm sizes), the shift to triple-cropping is predicted to be highly advantageous, comparatively benefitting all indicators bar sediment deposition. The aggregate movements between farm sizes are visualised in Fig. 4. This comparative analysis highlights the presence of system dynamics which differentiate outcomes between farm sizes; below we explore the internal drivers of this process.

During the model evaluation detailed in Section 4.3.2 we found that the model systematically overestimated the farming efficiency that triple-cropping farmers were able to achieve. We note that the implications of this inaccuracy for our findings are simply to strengthen the preferentiality of double-cropping over triple-cropping for lower quartile size farms, and to make the net change for median size farms negligible. But, there are no ramifications for the comparative conclusions which can be drawn from the model.

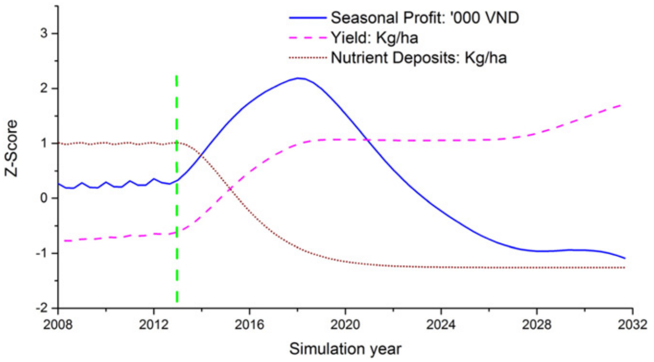

Fig. 3. An illustrative run of policy 1 for a farm of median size, without random variation applied. Shown: the seasonal profit of the farmer (smoothed solid line); the quantity of sediment-bound nutrients available to crops each season (smoothed dotted line); and the seasonal rice yield (smoothed dashed line). The three year (nine season) smooth is applied to improve the visualisation of the double-cropping system which would otherwise present with one fallow season every three seasons. The chosen indicators have been converted to *Z*-Scores, i.e. the number of standard deviations each value is from the mean.

The source of the income and debt penalty imposed by the triple-cropping system (policy 1) on poorer (smaller) farmers lies in the increased total and proportional artificial fertiliser application required by the addition of the third crop, and the loss of free sediment-bound fertilisation. The combination of lost free sediment-bound nutrients and the addition of a third rice crop results in an average increase in *annual* artificial fertilisation of 87% when comparing double (policy 2) to triple (policy 1) cropping. The cost of this increased demand for artificial fertilisation is greater on poorer farmers because the model predicts they operate at a lower level of input efficiency. Averaging across the testing period of our model it is seen that under the triple-cropping system (policy 1) LQ farmers were at approximately a 9% input efficiency disadvantage against UQ farmers whereas, under double-cropping (policy 2), their disadvantage reduces to 5% — this difference being a result of the farmers' increased economic capacity to invest in efficiency-enhancing technology under policy 2. The dynamic implication of this phenomenon is that, when combined with the finer margins that smaller-scale farmers operate on, triple-cropping (policy 1) farmers are unable to build up a large enough contingency fund to protect themselves against the model's stochastic fertiliser price spikes. In other words, the shift to triple-cropping reduces the economic resilience of poorer farmers in particular. This phenomenon is examined in more detail in Fig. 5. Notably, the debt spikes which result are found almost exclusively later on (beginning around 6–9 years from policy implementation) in the simulation meaning that evaluations of the (apparent) success of the transition to triple-cropping made in the aftermath of the shift might offer a misleading assessment of its performance over the long term. Moreover, Fig. 5 hints that once the farmer's economic resilience is broken, the implications are greater than just a one off loan being taken out, with debt often recurring in subsequent seasons.

The model also contributes operational insight into the reasons for the 6–9 year lag in the onset of debt. In Fig. 3 it can be seen that for the period between 2–4 and 6–9 years after implementation of triple-cropping farmers enjoy a period of substantial financial success. This success is harder to detect when the smooth is removed from the model outputs, as in Fig. 6A–B, as it is sourced from the continuous rather than staggered nature of the farmer's profits. Input costs do not instantly respond to the increased number of rice crops thanks to the buffer of the nutrient rich deltaic soil that is maintained by sediment deposition, as shown in the example simulation (Fig. 6B). However, the model suggests that this boost in profits is inevitably followed by a decline, initially relatively rapidly, then more slowly, through to the simulation end. This decline can be linked to the farmer using up the buffer of natural fertilisation provided by sediment deposition and transitioning to what is sometimes termed an 'open throughput' system (Berg, 2002) that is entirely reliant on artificial fertiliser inputs. This, in turn, has significant economic ramifications. As the sediment buffer declines the burden on artificial fertilisation increases, and the farmer must then identify the optimum level of fertilisation in a context of increasing and variable fertiliser prices (Fig. 6C), a process which lasts beyond the point at which sediment-bound nutrients are depleted.

Another key factor controlling farmers' success (or otherwise) lies in their ability to sustain their technological capacity and hence input efficiency. The model simulations identify two mechanisms that control the level of investment in technological advancement. The example simulation in Fig. 6 highlights the first mechanism: low profit periods (labelled D) reduce a farmer's ability to invest in their technological capacity and lead to a slump (labelled E) which, particularly under triple-cropping, takes some time to recover from. The second factor, which explains why this slump is harder to recover from under policy 1 and contributed to the lower technological capacity seen under policy 1 versus policy 2

Table 7
Four policies scored comparatively for three farm sizes: LQ: Lower Quartile, M: Median, UQ: Upper Quartile. Scoring is presented on a simplified comparative scale containing five ratings (−,−,0,+,++) where '–' represents the lowest scoring policy and '++' the highest.

			Total Rice production	Government Profit	Total sediment deposition	Disposable income	Income stability	Total debt	Debt prevalence
LQ	Triple-cropping	1	++	++	−	−	−	−	−
	Double-cropping	2	−	−	++	++	++	++	++
	3-3-2	3	+	+	−	−	−	0	−
	High year opening	4	+	+	−	−	−	−	−
M	Triple-cropping	1	++	++	−	−	++	−	−
	Double-cropping	2	−	−	++	++	−	++	++
	3-3-2	3	+	+	−	−	+	−	−
	High year opening	4	+	+	−	−	+	−	−
UQ	Triple-cropping	1	++	++	−	++	++	++	++
	Double-cropping	2	−	−	++	−	−	+	0
	3-3-2	3	+	+	−	−	+	−	−
	High year opening	4	+	+	−	0	+	−	−

(for median and LQ size farms), related to the lower profit margins per rice growing season. Farmers only invest in technology when the seasonal surplus is sufficient for them to feel it worth the risk (the risk being insufficient backup funds resulting in the future accrual of debt). Policy 1 involves continuous cropping of low surplus seasons with a high risk of unexpected input costs; policy 2 involves two high surplus seasons followed by lower risk of unexpected costs, giving farmers greater security to invest.

The simulation's suggestion that An Giang farmers are either currently, or likely soon will be, suffering from an increasing debt burden is one that can be substantiated in the literature and therefore provides an additional validation of the model. The debt issues faced by poorer farmers in particular have been mentioned in previous qualitative research (e.g. Garschagen et al., 2012), with one study estimating that up to 87% of a commune can rely on money lenders (Swain et al., 2008). Given the relatively recent conversion of many communes to triple-cropping (while conducting our survey we encountered communes that had converted as recently as 2013), the delay in the onset of debt may mean this issue has not yet been realised or appreciated to its fullest extent.

5.2. Implemented variant policies

In this section we use the SDM to explore the effectiveness of a variant rice cultivation strategy that has been implemented to alleviate the negative impacts described above. Specifically, the 3–3-2 cropping rotation is the only policy implemented which directly addresses the role of sediment exclusion in the system, albeit as of 2014 it was only found in 2 of the 9 An Giang communes surveyed. From Table 7 and Fig. 4 it can be seen that, comparatively, the 3-3-2 rotation (policy 3) did not excel in any of the key indicators. The 3-3-2 cropping system attempts to find a middle ground between the two extremes of high and low sediment deposition. However, importantly the 3-3-2 rotation involves *regular* switching between cropping systems, and it is in this regular switching that its poor performance lies. Every third year, independent of the magnitude of the flood and hence sediment deposition potential experienced in that third year, the farmer sacrifices a crop in order to receive sediment. This means that in the event that the third year coincides with a low flood, sediment deposition potential is reduced relative to a system that switches responsively to maximise sediment deposition potential. The sediment deposited holds both short and medium term value. However, the total short term value the farmer gains from the sediment, combined with income from off-season activities, is lower than the income they would gain from a season of rice (although, when the medium term gain is considered the net gain may be greater). The triple-cropping system requires that the farmer hold sufficient (and significant) short-term funds to cover the increased fertilisation costs. Examining the model simulations we found that the lower income obtained in the short-term during the double-cropping season reduces the contingency funds available to the farmer for the next year's fertilisation costs. Thus, farmers struggle to fund their input costs in the cropping seasons directly following a fallow season, and their resilience to high fertiliser prices therefore declines. Fig. 7, which shows the probabilities of debt being incurred at different stages, illustrates this issue. As a result, the 3-3-2 system (policy 3) ranks poorly in terms of debt prevalence. Again, this phenomenon only tends to have an impact after the initial income boost the farmer receives from switching to triple-cropping subsides, which our model indicates occurs after 6–9 years. However, it should be noted that the precise length of this lag is primarily influenced by the parameter which determines the time between nutrient deposition and its availability for plant uptake; this parameter was one of five identified as having a notably weaker evidence base in Section 4.3.1. In contrast to policy 1, where triple-cropping performs notably worse for land-poor farmers, the 3-3-2 system's performance is uniformly poor across all farm size categories.

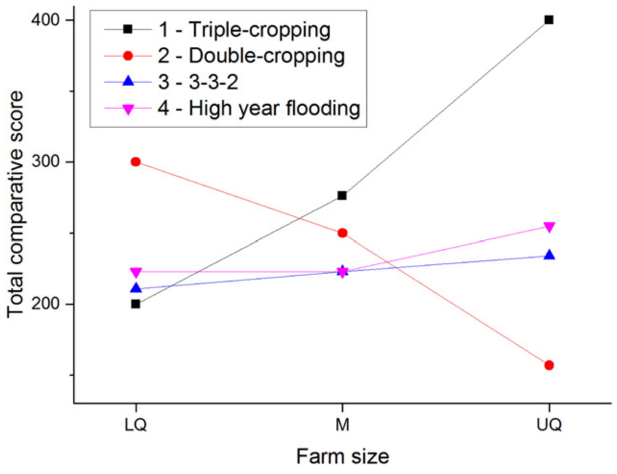

Fig. 4. The comparative score (out of 100) of each policy in each indicator has been aggregated for each of the policies and for the three farm size classes. Comparisons can be made between the performances of each policy at different farm sizes (lower quartile (LQ), median (M) and upper quartile (UQ) of the 195 farms surveyed by Chapman et al. (2016). Indicators have not been weighted.

5.3. Proposed variant policies

Here we ask: how do other, proposed, policies affect the system's dynamics and how do they compare with the status quo? To address this question we tested a model set-up (policy 4) in which the farmer performed double-cropping and allowed inundation and sediment deposition only in years with higher sediment deposition potential. Theoretically this policy would ensure the fallow season was optimised for maximum benefit and we hypothesised that this would reduce some

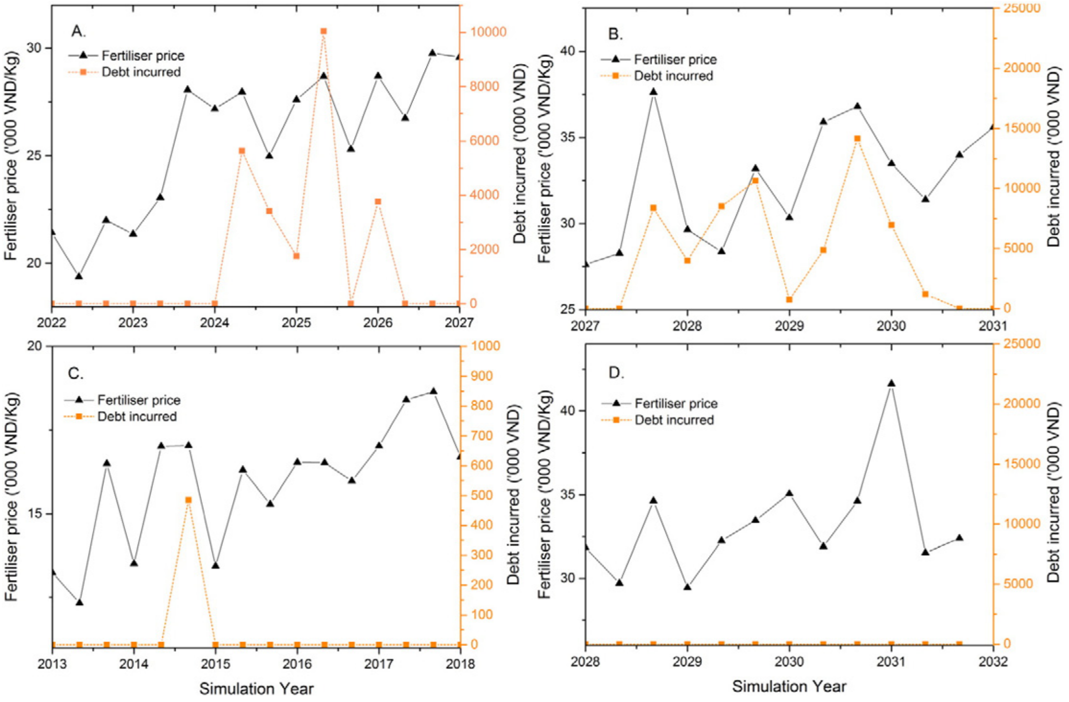

Fig. 5. Four examples of peaks in fertiliser prices. A, B, and C show LQ simulations, D shows a UQ simulation. In A and B we see peaks in fertiliser prices causing debt spikes. Commonly these spikes occur later in the simulation and the initial spike tends to have a knock-on effect on subsequent seasons. Graph C is a rare example of a small early-simulation debt spike caused by two localised price spikes that does not have a knock-on effect. In graph D we see an example of a UQ size farmer coping with a severe price spike without incurring debt.

of the negative traits of the 3-3-2 rotation (policy 3). Indeed, when all indicators are aggregated policy 4 is seen to offer an improvement relative to policy 3 (Fig. 4). However, policy 4 results in farmers incurring marginally greater debt problems (Table 7). The phenomenon causing this is now familiar. While fallow seasons are smaller in number under policy 4 versus policy 3, the random nature of when peak flood events occur occasionally means successive years of double-cropping. Such occurrences have a significant impact on farmers' economic reserves and result in debt in the subsequent season in which the farmer returned to triple-cropping.

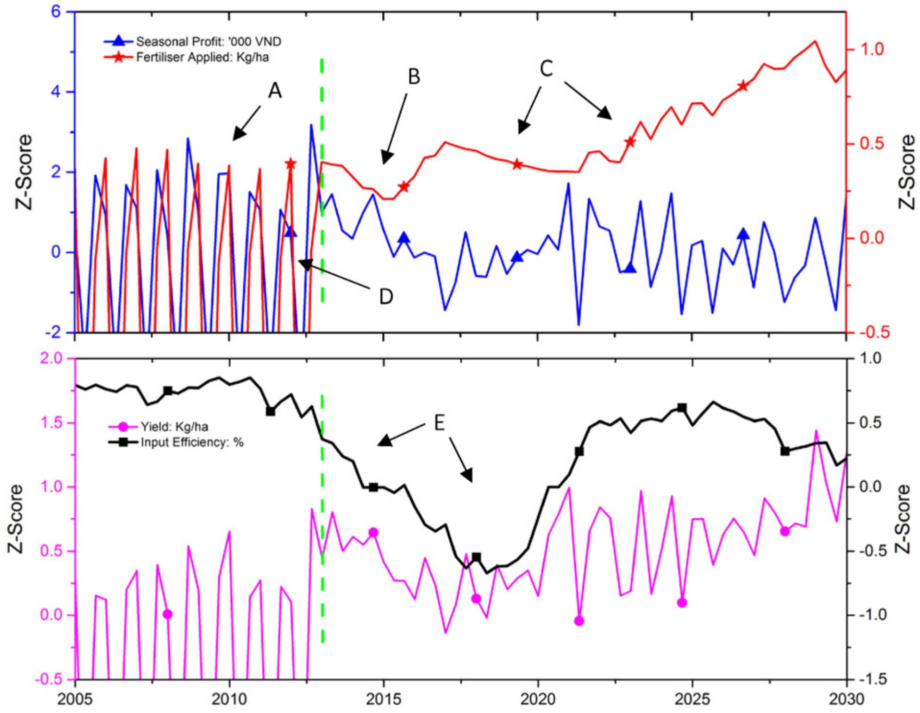

Fig. 6. Four simulation indicators (seasonal profit, fertiliser applied, yield, and input efficiency) shown for a sample run of a farm of median size operating Policy 1 with random variation on and no smoothing applied. In green, the point at which the switch in cropping pattern took place is highlighted. The chosen indicators have been converted to *Z*-Scores, i.e. the number of standard deviations each value is from the mean. Some key features are labelled.

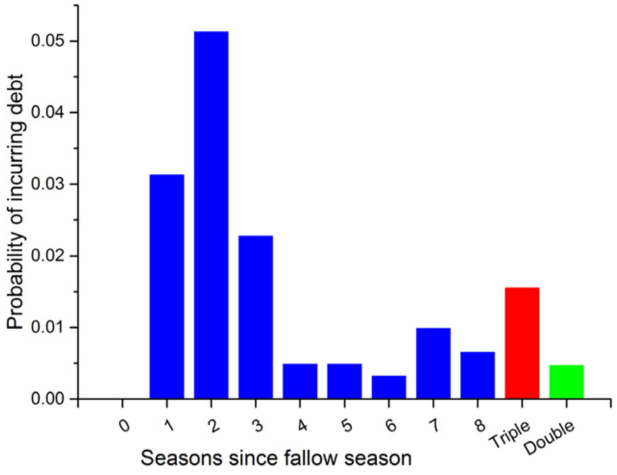

Fig. 7. The probability of a median size farmer falling into debt during the policy simulation period on a given season under policy 3. For comparison the average probabilities for the triple and double cropping policies are shown.

Despite the above caveat, when all of our indicators are aggregated, policy 4 performs better than policy 3 across all farm size categories (Fig. 4). This is a direct consequence of the optimisation of sediment-bound nutrient potential, which improves the long term yield to fertiliser ratio. Furthermore, while opinions differ on the best way to protect local livelihoods from intensifying fluvial floods, most agree that controlled inundation during intense flood events is an effective mechanism, particularly for protecting livelihoods downstream of the paddy compartments. This additional benefit would further increase the preferentiality of policy 4 against the alternatives if it were included in our aggregate scores (Fig. 4).

6. Discussion and conclusion

In this paper we have established, tested and applied a new model capable of analysing different adaptation policies in terms of how their different dynamics encourage or discourage a just and resilient system in deltas. Particularly, to our knowledge, this is the first such model to integrate the socioeconomic role of fluvial sediment deposition. The new model performs well in simulating observed behaviours of the system, substantiating and providing quantitative, operational, evidence towards concerns about the prevalence of debt in the adapted rice-cropping system of An Giang. With this study we have therefore shown the operability of a system dynamics approach which evaluates disparate cross-disciplinary factors controlling adaptation success. We argue that this approach has wide transferability, offering the potential for rapid systems assessment in regions facing similarly intense changes, and particularly the delta context, which is of high importance to global food security. Notable candidate systems for the application of this model might be found in the other South/Southeast Asian deltas under threat, such as the Irrawaddy, Chao Phraya, and Ganges-Brahmaputra (Auerbach et al., 2015).

A key outcome of our modelling is to highlight an operational mechanism through which the loss of fluvial sediment, combined with lower input efficiency and high and variable fertiliser prices, can force a greater debt burden on poorer farmers operating the triple-cropping rice cultivation system. The system has been the focus of rapid recent expansion, and hence this finding raises significant concern of a reduction in the resilience of poorer groups to future fertiliser price growth and spikes. Furthermore, we present evidence that through these mechanisms the high dyke adaptation which underpins the triple-cropping system may actively increase the efficiency gap, and hence wealth gap, between the wealthiest farmers and the rest of agricultural society. Our findings suggest that although the recent switch to triple-cropping offers a short-term boost in income, farmers face a significant risk of a decline in productivity and profitability subsequently. Indeed, our evidence suggests that from a local, medium to long-term, perspective there is negligible benefit for the majority of farmers making the triple-cropping shift. The benefits of triple-cropping are instead felt overwhelmingly at a macro-economic scale through the benefits for total rice production, the governmental export income this generates, and in the financial gains made by the land-wealthier farmers with the margins and contingency to cope with shocks in fertiliser prices. Policy makers therefore need to weigh these benefits against the flood protection and delta sustainability advantages of alternative policies (such as policy 4, the strategic flooding of paddy compartments during high flood years) which facilitate sediment deposition and offer better outcomes for poorer farmers. In these respects our study provides valuable detail and support to the findings of the Mekong Delta Plan (2013) and specifically its recommendations to implement strategic controlled flooding of northern regions of the Vietnamese Mekong delta (our policy 4, Fig. 4). Moreover, it builds on a body of literature (e.g. Szabo et al., 2015) emphasising the important role of wealth inequality in determining society's ability to cope with environmental change, and importantly also adaptations, in delta regions.

The Mekong delta (and our case study province, An Giang) is a key region in terms of its contribution to global food security, its large population, and the intensity of the environmental change and development pressures it is subject to. Achieving wellbeing for all those dependent on such regions is a major policy challenge (Dearing et al., 2014). Our exploration of the dynamics of different policies and their implications across multiple objectives for the Mekong delta system highlights the difficulty of balancing different objectives to find what Dearing et al. (2014) term “safe and just operating spaces” for society. Nevertheless, our use of a novel system dynamics approach towards adaptation decision making, in a context of double exposure to climate change and development impacts in river deltas, offers a step forward towards meeting this challenging objective.

Acknowledgements

The authors wish to extend their thanks to Professor P.I. Davidsen and the System Dynamics group at the University of Bergen for their support with the modelling process, and the University of Southampton for PhD funding. S.E.D's contribution to this paper was supported by award NE/JO21970/1 from the UK Natural Environment Research Council (NERC).

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2016.02.162.

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