Analysis

Sustainable value of degraded soils in China's Loess Plateau: An updated approach

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ABSTRACT

China's Loess Plateau is a highly distressed region where intensive crop production has been undermined by high soil erosion rates that threaten the long-term livelihood of its inhabitants. Regional policy goals aim to balance economic performance with the sustainable use of natural resources. From a practical perspective, challenges arise when measuring sustainability levels that mix multiple dimensions, scales, and benchmarks. This study addresses these challenges by comparing the sustainability of agricultural systems across varied crops, land types, and cropping techniques in China's Loess Plateau. Sustainability levels for each system are compared to benchmarks using data envelopment analysis, which is then used to calculate a sustainable value (SV). The SV approach provides a monetary measure of sustainability that includes economic, environmental and social dimensions. Results demonstrate that the most sustainable agricultural systems in the Loess Plateau involve machine intensive cropping systems, a corn–soybean–corn rotation, mulching, furrows ridging, and bench terracing.

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1. Introduction

Assessing the sustainability of agricultural systems is challenging because measurements frequently mix multiple dimensions, scales, and benchmarks. This study uses data envelopment analysis (DEA) to develop benchmarks for comparing the sustainability of different agricultural systems and cropping techniques with a measure of sustainability called sustainable value (SV). Incorporating DEA into the sustainable value (SV) approach expands upon the work of Figge and Hahn (2004, 2005), who first introduced SV in the journal Ecological Economics. SV calculations integrate human, natural resource, and financial dimensions to generate a monetary measure of sustainability.

The Loess Plateau provides a rich context to illustrate how sustainability measurements can be used to assess natural resource management trade-offs. It is a highly distressed region where intensive crop production is undermined by high soil erosion rates that threaten the long-term sustainability of the land and local food production (Lu, 2000; Lu et al., 2003). The Loess Plateau is one of the most severely degraded areas in the world, with over 60% of its land subjected to soil degradation and an average annual soil loss of 20–25 t/ha (Shi and Shao, 2000). Land use changes are often extreme. Much of the agricultural land has already been planted to trees through the Grain for Green program (Feng et al., 2005). However, converting from cropland to trees is an extreme conservation measure that generates little economic return to farmers who make a living mostly on their land. Many have migrated to urban areas in order to compensate for lost farm jobs, leading to other unintended consequences. In some cases child-care and other parental activities have been left to the elderly or older children (Li et al., 2012). Rather than focusing on extreme land use changes, the analysis presented in this paper investigates how to balance environmental objectives with continued crop production.

Many frameworks have been proposed to measure sustainability. Macro scale proposals include the Green National Product (Cobb and Cobb, 1994), Ecological Footprints (Wackernagel and Rees, 1998), and Genuine Savings (Hamilton and Clemens, 1999). These methods are generally used to readjust Gross Domestic Product or Gross National Product calculations to account for net changes in environmental degradation. While ecologically minded organizations promulgate these alternative accounting approaches, the frameworks are not widely applied in China. Unlike the DEA/SV method proposed in this paper, these macro-level approaches do not explicitly map the value of meeting different environmental targets (like reduced nitrogen loss) that are affected by local and regional agricultural production practices.

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SV is used to calculate net sustainable values, rather than the environmental burden imposed by natural resource use. First presented in Ecological Economics by Figge and Hahn (2004, 2005), SV is based upon Capital Theory (Costanza and Daly, 2003; Harte, 1995; Pearce and Atkinson, 1993; Prugh et al., 1999; Stern, 1997; Victor, 1991). SV assesses the sustainability of a proposed or existing system by comparing the opportunity cost of using capital (e.g. financial, human, and natural capital) in that system rather than a predetermined benchmark.

SV can be used to evaluate the effectiveness of local or regional natural resource management decisions. For example, Van Passel et al. (2007) apply the SV approach to the Flemish dairy industry, finding the method to be useable and workable for smaller enterprises. Two years later the authors improved upon the method by applying a parametrically estimated efficiency frontier to provide individual benchmarks for each system (Van Passel et al., 2009).

The research presented in this paper takes advantage of the SV approach to study cropping systems in the Loess Plateau, but refines it by creating discrete, customized individual benchmarks using a DEA. The DEA allows for comparison between similar systems and creates a discrete benchmark that is specifically comparable to that system. In contrast to previous studies that chose a single "best" benchmark, or a parametrically estimated frontier, the DEA method allows us to create a non-parametric frontier of benchmarks that takes into account the most efficient use of capital for each unique system (crop type, land type and cropping techniques). The SV for over 2000 cropping systems reviewed for the Loess Plateau is recorded in a series of comparison matrices and organized by crop type, cropping technique or land type. These matrices are then used to determine which management practices, like rotation or terracing, have the greatest impact on sustainability.

Although this would be the first known integration of the DEA with SV methods, the DEA method has been applied to other sustainability measures. For example, it has been used to compute environmental efficiency (De Koeijer et al., 2002; Wossink and Denaux, 2006). Environmental efficiency is formulated in the same way as technical efficiency except that environmental impacts, rather than observed inputs, are calculated. One limit of environmental efficiency is that it becomes difficult to measure environmental impacts. Eco-efficiency, defined as the ratio of a created value over the environmental impact, is another popular indicator for measuring sustainability that used DEA (Jollands et al., 2004; Picazo-Tadeo et al., 2011). According to Van Passel et al. (2007), the rebound effect is one major shortcoming of eco-efficiency. The rebound effect means that advances in environmental performance may be over stated because better eco-efficiency may also lead to growth and thus increase the use of environmental resources.

The paper is organized, as follows: The methodology, presented in Section 2, updates Figge and Hahn's (2004, 2005) SV approach by introducing frontier benchmarks estimated with DEA. Section 3 contains a description of the Loess Plateau study area and the simulation data, created from the Environmental Policy Integrated Climate (EPIC) model (Gassman et al., 2005; Williams et al., 2006). This simulation is conducted on more than 2000 different cropping-system variations that are based upon Lu's original work (2000) and a subsequent publication that uses approximately 500 of these cropping systems (Lu et al., 2003). The sustainability measurements evaluate different combinations of crop rotations, production situations, terracing techniques, tillage techniques, crop residue management techniques, mechanization levels, and land units. The empirical results are reported in Section 4. Discussion and conclusions are provided in Sections 5 and 6, respectively.

2. Methodology

2.1. Summary and Example of the SV Approach

2.1.1. The Original Figge and Hahn SV Approach

Figge and Hahn (2004, 2005) developed the SV approach based upon principles and definitions from the theoretical finance literature.

The SV approach measures the opportunity cost of each form of capital investment (financial, human, and natural capital). In the original papers, the opportunity cost is the value created by a unit of capital that is produced in the market (system benchmark) instead of a unit of capital used in a cropping system, which is the focus of this example. This section presents an illustrative example of Figge and Hahn's original SV approach, with hypothetical values presented in Table 1, followed by a discussion in the text.

A cropping system produces a positive economic value if it creates more value than would have been generated by investing the same amount of capital in the market. In this example, the objective is to evaluate the opportunity cost of using capital in comparison to a benchmark cropping system, rather than a market. Figge and Hahn's SV approach incorporates opportunity cost measurements to circumvent an aggregation problem when assessing different forms of capital.

As shown in Table 1, a hypothetical benchmark system (System 0) that is known to be an efficient user of human capital, natural capital (expressed in kg/ha soil erosion) and financial capital might produce a value added of $1000/ha. Whereas, an alternative system (System 1) might produce only $600/ha. These systems are not directly comparable because they use different amounts of capital. For example, System 1 has less soil erosion compared to the benchmark, but has more erosion per unit of value. The SV approach determines how much the comparison system, System 1, would need to earn to offset the opportunity cost of diverting capital from the benchmark. SV is the difference between what the system earns in value added ($600/ha) and what it needs to earn ($900/ha) in order to offset the sum of the opportunity cost of capital. Therefore, SV is − 300 in this example.

Furthermore, Figge and Hahn define sustainable efficiency (SE) as the ratio between the value added and the cost of sustainability capital for the system. In this case SE is 0.67 ($600/$900). The system under consideration could produce another $300/ha, or 33% more, if capital resources were used more efficiently (sustainably).

The first step in the SV process is to establish the opportunity cost of using capital in a benchmark. If a unique benchmark is assigned to each observation, opportunity cost for the sth form of capital in the ith cropping system can be computed by:

$$\text{Opportunity cost}_{s,i} = \frac{\text{Value added}_{s,i,benchmark}}{\text{Capital}_{s,i,benchmark}} \qquad (1)$$

Table 1
Sustainable value and sustainable efficiency example.

	System 0 (benchmark)	System 1 (crop system)
Basic data		
Value added($/ha)	$1000	$600
Human capital (labor/ha)	10	12
Natural capital (kg/ha soil loss)	200	150
Financial capital($/ha)	$2000	$1500
Opportunity cost of:		
Human capital	$100 = $1000/10	–
Natural capital	$5 = $1000/200	–
Financial capital	$0.5 = $1000/2000	–
Value spread for:		
Human capital	0 = ($1000/$10)–$100	−$50 = ($600/12)–$100
Natural capital	0 = ($1000/$200)–$5	−$1 = ($600/150)–$5
Financial capital	0 = ($1000/$2000)–$0.5	−$0.1 = ($600/$1500)–$0.5
Sustainable value	0	−$300[a]
Cost of sustainable capital	$1000 = $1000–0	$900 = $600–(−$300)
Sustainable efficiency ratio	1.0 = $1000/$1000	0.67 = $600/$900

[a] As expressed in Eq. (3). Sustainable value calculated as: −300 = (1/3)*[(−50) *12 + (−1)*150 + (−0.1)*1500].

The opportunity cost of human capital in Table 1 is $100/ha, computed by dividing the value added from System 0 (i.e. $1000/ha) by the human capital from System 0 (i.e. $10/ha). Value added is simply a parameter reflecting the system's earnings and is equal to crop revenue minus intermediate consumption.

The value spread for the sth form of capital in the ith cropping system reflects the additional value created using capital for the cropping system, compared to the benchmark. It can be calculated by:

$$\text{Value spread}_{s,i} = \frac{\text{Value added}_{s,i,\text{benchmark}}}{\text{Capital}_{s,i,\text{benchmark}}} - \text{Opportunity cost}_{s,i} \qquad (2)$$

The value spread for human capital in System 1 is –$50, calculated by dividing value added from the system by the units of capital used by the system ($600/$12) and subtracting the opportunity cost of using the capital in the benchmark ($100).

The SV created by firm i can be calculated by adding up the value spreads from every form of capital $s = 1…,n$ (Van Passel et al., 2007) as follows:

$$\text{Sustainable value}_i = \frac{1}{n}\sum_{s=1}^{n}\left(\text{Value spread}_{s,i} x \text{ Capital}_{s,i}\right) \qquad (3)$$

Dividing by n does not serve to weight different forms of capital but only to avoid multi-counting of value creation (Figge and Hahn, 2005). The SV of System 1 is −$300/ha, as shown in Table 1. A negative value implies that switching to the system away from the benchmark would reduce sustainability.

SE for the ith cropping system is the ratio between the value added and the cost of sustainability capital for the system (Figge and Hahn, 2005). Its mathematical form is:

$$\text{Sustainable efficiency}_i = \frac{\text{Value added}_i}{\text{Cost of sustainable capital}_i} \qquad (4)$$

The cost of sustainable capital is the added value that could have been produced in the benchmark with the same amount of capital used by the system. This is calculated using the value added by System 1 ($600/ha) minus the SV of System 1 (−$300/ha), which sums to $900/ha. SE is simply the ratio of value added for the system as compared to the benchmark, or $600/$900 = 0.67. Compared to the benchmark, System 1 is not using capital efficiently. In this example, SE indicates whether farm practices are using soil as efficiently as possible, while accounting for adjustments in other forms of capital.

2.1.2. Steps for Calculating SV and SE

This section provides a summary of steps for calculating SV and SE, which are applied to the Loess Plateau example. According to Van Passel et al. (2009), the SV and SE can be calculated in three steps. First, the scope of the analysis is determined. The data used in the presenting study employs 2006 distinct cropping systems as entities (also referred to as "firms") to create sustainable value. The entities all employ all three forms of capital. Different cropping systems are characterized by various technologies and practices such as crop rotations and terracing techniques.

Second, relevant resources must be identified. In the context of sustainable development, the weight of relative importance of the capital forms used by a firm can be judged by the scarcity or degree of depletion of the capital (Figge and Hahn, 2005). Over 60% of land in the Loess Plateau is subjected to soil degradation. Nitrogen loss is associated with soil loss. Thus, in this study soil and nitrogen are recognized as two forms of natural capital. Soil and nitrogen data are rare to observe at the farm level or national level, which strengthens the rationale for utilizing a SV measurement. Fortunately, the simulation model in Lu et al. (2003), which is verified by experiments, provides extensive and realistic estimates of soil and nitrogen losses associated with various cropping practices. In addition to natural capital, financial capital and human capital are also taken into account through enterprise budgeting.

Third, appropriate benchmarks must be determined. Four possible benchmarks were proposed by Van Passel et al. (2007). First, the weighted average of a sample can be used. For example, cropping systems with conservation practices can be chosen to calculate benchmarks. Second, a super-efficient firm that uses every single type of capital in the most efficient way can serve as the super-efficient benchmark. In practice, a super-efficient cropping system is highly unlikely. Third, a performance target can be used as a benchmark. A performance target example given by Van Passel et al. (2007) is 150 kg nitrogen per ha for the farm gate nitrogen surplus for dairy farms. Fourth, the unweighted average of all firms in the sample can be used as a benchmark.

2.1.3. Using the DEA Method to Formulate Benchmarks

The benchmark choice reflects a normative judgment of sustainable development, and thus biases the way in which the SV is interpreted (Van Passel et al., 2009). Benchmarks should therefore be chosen with great care. Since the goal of this study is to identify the most sustainable cropping systems, the best performance benchmark is preferred. A performance target may also be appropriate, but it may not be easy to specify the reasonable target level. In this paper, many possible cropping systems for the Loess Plateau are considered, so a frontier is constructed for all the possible cropping systems. The frontier takes into account the most efficient use of capital for each unique system, rather than assuming that there is a single best system.

Instead of using the parametric frontier benchmark proposed by Van Passel et al. (2009), this study adopts a non-parametric DEA to determine benchmarks. Both parametric and non-parametric approaches have been proposed in the frontier literature (Reinhard et al., 2000). Data noise can be taken into account in the parametric approach, but specification error may arise from the choice of the functional form. The DEA approach is chosen to avoid functional form specification error. The dataset incorporated in this study is simulated from the EPIC model, which is described in greater detail in Section 3. Data noise is not expected to play a significant role in the estimation of the production frontier in this study because simulated data do not present sampling bias; that is, the simulated data can be readily replicated. The DEA method is also more computationally efficient, especially when multiple capital types are considered in the production process. Another advantage is that a unique frontier benchmark is specified for each cropping system through the consideration of each technology possibility. Mathematically, the DEA benchmarks can be defined, as follows:

Denote all inputs by $x \in R_+^N$, all desirable outputs by $y \in R_+^M$, and all undesirable outputs by $w \in R_+^J$. The technology set S can be defined as:

$$S = \{(y, w) : x \text{ can produce } y \text{ and } w\}. \qquad (5)$$

The key tool used to formulate the best performing benchmark is the input distance function, denoted by $D_i(y, w, x)$. It can be defined as (Färe et al., 1996):

$$D_i(y, w, x) = \max\left\{\rho : \left(\frac{x}{\rho}, y, w\right) \in S\right\} \qquad (6)$$

This function measures the extent, denoted by ρ, that inputs can be decreased to reach the efficient frontier. The assumption $D_i = 1$ implies that the observation is on the frontier, it is efficient, and no reduction in inputs is possible. The assumption $D_i > 1$ means that the observation will be efficient if the inputs x are reduced to x/D_i. As Färe et al. (1996) pointed out, since the same factor ρ is applied to all inputs, only an equiproportional reduction of inputs is considered.

Suppose there are $i = 1,…,I$ observations on N inputs, M desirable outputs and J undesirable outputs. Based on the dataset used in this

study, the technology set can be constructed as follows (see Färe et al., 1996):

$$S = \left\{ \begin{array}{c} (x, y, w) : \sum_{i=1}^{I} \lambda_i x_{n,i} \leq x_n, \ n = 1, ..., N, \\ \sum_{i=1}^{I} \lambda_i y_{m,i} \geq y_m, \ m = 1, ..., M, \\ \sum_{i=1}^{I} \lambda_i w_{j,i} = w_j, \ j = 1, ..., J, \\ \lambda_i \geq 0, \ i = 1, ..., I \end{array} \right\} \quad (7)$$

The input distance function for each observation can be computed by solving the following linear programming problem:

$$[D_i(y_i, w_i, x_i)]^{-1} = \min_{\rho, \lambda} \rho \quad (8)$$

$$s.t. \sum_{i=1}^{I} \lambda_i x_{n,i} \leq \rho x_n, n = 1, ..., N \quad (9)$$

$$\sum_{i=1}^{I} \lambda_i y_{m,i} \geq y_m, m = 1, ..., M \quad (10)$$

$$\sum_{i=1}^{I} \lambda_i w_{j,i} = w_j, j = 1, ..., J \quad (11)$$

$$\lambda_i \geq 0, i = 1, ..., I \quad (12)$$

Therefore, the opportunity cost for the sth form of capital in the ith firm with a DEA benchmark can be updated by:

$$\text{Opportunity cost}_{s,i} = \frac{\text{Value added}_{s,\text{benchmark}}}{\text{Capital}_{s,\text{benchmark}}} = \frac{\text{Value added}_i}{\text{Capital}_{s,i}/D_i} \quad (13)$$

2.2. Cropping System Impacts on Sustainability

SV and SE do not by themselves show which crops or practices contribute most to sustainability. However, that information can be claimed through ex-post analysis. This section describes how different conservation techniques are aggregated into a linear regression to derive the marginal impacts of crop type, cropping technique or land type on SV and SE. The following simple linear regression is formulated based upon data collected by Lu et al. (2003) in order to analyze which cropping practices and conservation techniques enhance or deplete sustainability:

$$Y_i = \beta_0 + \beta_1 ROT_i + \beta_2 RES_i + \beta_3 CONT_i + \beta_4 PRO_i + \beta_5 MEC_i \\ + \beta_6 TER_i + \beta_7 SLP_i + \varepsilon_i \quad (14)$$

where the dependent variable Y_i is the SV or SE of the ith cropping system, calculated from the SV approach. Different cropping practices, land units and conservation techniques (shown in Table 2, and further described in Section 3) are represented by sets of dummy variables of the ith cropping system. ROT_i is a set of dummy variables for crop rotations, RES_i for crop residue management, $CONT_i$ for contouring or furrow ridging, PRO_i for production situations, MEC_i for mechanization level, TER_i for terracing, and SLP_i for land steepness. All β's are parameters to be estimated. ε_i is the error term.

The estimated parameters capture the marginal contribution of alternative conservation techniques to either SV or SE. For example, the dummy variable RES_i takes the value of 1 if mulching is adopted; otherwise, it equals zero. The coefficient β_2 in front of RES_i is expected to be positive. In the SV model the interpretation is that crop mulching contributes β_2 dollars to SV compared to a non-mulching technique. Some conservation techniques have more than two options. For example, crop rotation techniques include 17 alternatives in this study, and therefore 16 dummy variables are used for rotation in the regression model. The coefficients corresponding to the 16 dummy variables are the marginal contribution of each cropping rotation, compared to the basis rotation.

Table 2
Cropping systems identified and measured by Lu et al. (2003)[a].

Characters	Specifications
Crop rotation types[b]	Include 2 mono crops, 8 types of rotation without alfalfa and 7 types of rotation with alfalfa. The 2 mono crops are C and W; the 8 types of rotation without alfalfa are PsWC, CMPa, CSC, FWPaM, PsWCM, MSC, WPaMCF, MSMPa; and the 7 types of rotation with alfalfa are A3CM, A3CPaM, A3MPaM, A4MPaM, FA5MC, FWA4MC, A3MCPaCM.
Conservation techniques	Include 4 techniques: contouring & mulching, contouring & non-mulching, furrow ridging & mulching, furrow ridging & non-mulching.
Terracing techniques	Include 3 terracing situations: no terracing, bench terracing, and spaced terracing.
Land units	Include 5 units classified by land slope steepness: floodplains, gently sloped land, moderately sloped land, steeply sloped land, and very steeply sloped land.
Production situations	Include 3 situations with different availability of water and nutrients: sufficient water and nitrogen, water-limited and nitrogen-limited.
Mechanization levels	Include 2 levels: human and animal labor, semi-mechanization.

[a] A subset equal to 2006 of these 6120 systems (5*(2 + 7 + 8)*3*4*2*3) were used in Lu et al.
[b] A = alfalfa and years, C = corn, M = millet, F = flax, Ps = Summer Potato, Pa = Autumn Potato, S = soybean, W = winter wheat.

Policy makers, farmers, and farm advisors may be interested in comparing the SV and/or SE between any pair of the 17 rotations, or other differences in cropping systems, in order to advise farmers toward adopting more sustainable systems. Therefore, comparison matrices are constructed based on the regression results for cropping practices, land units and conservation techniques as estimated in Eq. (14), and further described in Section 3.

3. Data and Study Area

3.1. The Loess Plateau Study Area

The Loess Plateau is located between 34–40°N and 101–138°E in North China, covering an area of 0.65 million km^2, with a total population of 108 million (National Development and Reform Commission, NDRC, 2010). It has an extremely hilly loess landscape and a semi-arid climate, with extensive monsoonal influence. The mean annual rainfall is mostly between 350 and 550 mm, of which more than 70% occurs in the rainy season of June to September. It is characterized by steep sloping lands, which are marginally suitable for cropping. The rate of soil loss is generally more than 50 t/ha in the hilly area (Lu et al., 2003). As noted in the introduction, although land use changes may be extreme, the focus of this paper is to investigate how to balance environmental objectives with continued crop production.

3.2. Data

Lu et al. (2003) identified the cropping systems in Ansai County of the Loess Plateau. A summary of these systems is presented in Table 2. Their dataset includes 2006 cropping systems that are comprised of different combinations of 5 land units, 17 crop rotations, 3 production situations, 3 terracing techniques, 2 tillage techniques, 2 crop residue management techniques and 2 mechanization levels. Corresponding outputs of interest (e.g. yield and soil erosion) were simulated for each system using the Environmental Policy Integrated Climate (EPIC) model and validated with the experimental data as described by Lu et al. (2003). EPIC is a comprehensive simulation model designed to predict the effects of management decisions on soil, water, nutrient and pesticide movements and their combined impact on soil loss, water quality and crop yield (Gassman et al., 2005; Williams et al., 2006). It consists of weather, surface runoff, water and wind erosion, nitrogen leaching, pesticide fate and transport, crop growth and yield, crop rotations, tillage, plant environment control (drainage, irrigation,

fertilization, furrow diking, liming), economic accounting, and waste management. Lu et al. developed the comprehensive dataset regarding soil, weather, crop management, fertilizer and other parameters to meet the basic requirements to run the EPIC model. Hundreds of equations are applied in EPIC to then simulate processes such as crop growth and soil erosion.

As described in Section 2, in order to apply the SV approach with DEA benchmarks, the value added and capital need to be specified. As previously defined, crop revenue minus intermediate consumption is specified as "value added" in the SV approach. To cope with multidimensionality, it is assumed that each cropping system uses all forms of capital to produce value. Typically, natural capital is difficult to measure. However, the EPIC model provides an opportunity to measure soil loss and nitrogen losses directly. Nitrogen losses are estimated in EPIC through "runoff and sediment, nutrient movement by soil evaporation, denitrification, ammonia nitrification and volatilization, mineralization, immobilization, biological-fixation, contribution of rainfall and irrigation, and NO_3-N leaching Lu et al. (2003, p. 315)." Lu et al. note that most of the losses of N resulted from volatilization, runoff and soil erosion.

Soil loss and nitrogen loss from the EPIC model are treated as natural capital inputs in the production process. Labor is viewed as human capital. Financial capital is calculated by aggregating all conventional inputs, including seeds, nutrients (Nitrogen, Phosphorus and Potassium), biocides, irrigation if applicable, and farm equipment (including seeding machines, knapsack sprayers, plow, hoes, cutters and threshers).

Descriptive statistics of the data are given in Table 3. Revenue and cost data, except labor, are expressed in Chinese monetary units, the RMB. Natural capital, soil and nitrogen, are described in physical units. Financial capital and human capital are expressed in the RMB monetary units. On average, 5221 RMB/ha (828.7 US dollars) in revenue can be produced by a 3112 kg/ha soil loss and 15.3 kg/ha nitrogen loss, a cost of 1654 RMB/ha (262.5 US dollars, excluding labor) and 1390 RMB/ha (220.6 US dollars) for labor. Prices used to calculate aggregate value added and capital are taken from Lu et al. (2003) (Table 4). Prices are not updated to the current year to make these results comparable to Lu et al.'s study in 2003; input and output prices have changed at different rates during the past 10 years and some prices could not be recovered from Lu et al. This assumption does not affect lessons from this study.

4. Results

4.1. The DEA Benchmark

The four benchmarks proposed by Van Passel et al.(2007) are fixed to all firms. However, the DEA approach can assign a unique benchmark to each observation. The inputs of the benchmark corresponding to the ith cropping system are calculated by dividing the observed inputs from the ith cropping system by its input distance function. The technology set here is defined as 2006 distinct cropping systems that produce

Table 3
Descriptive statistics of value added and capital for 2006 cropping systems.

Variable	Terms in SV[a] approach	Mean	Standard deviation	Minimum	Maximum
Revenue (RMB/ha)	Used in "Value added" calculation	5221	1483	1446	12,594
Cost except labor (RMB/ha)	Used in "Value added" calculation	1654	776	506	4561
Soil loss(kg/ha)	Natural capital	3112	7480	0	69,838
Nitrogen loss (kg/ha)	Natural capital	15.3	9.4	0.01	57.6
Labor(RMB/ha)	Human capital	1390	682	87	2942

Source: Lu et al. (2003).
[a] SV = the sustainable value approach; 1 US dollar = 6.3 RMB at year 2012.

Table 4
Prices used to aggregate value added and capital[a].

Input name	Input price	Unit	Output name	Output price	Unit
Nitrogen (N)	2.9	RMB/kg	Corn	1.24	RMB/kg
Phosphorus (P)	7.8	RMB/kg	Millet	1.28	RMB/kg
Potassium(K)	4.8	RMB/kg	Wheat	1.40	RMB/kg
Biocide	40.0	RMB/kg	Soybean	2.40	RMB/kg
Human labor	10.0	RMB/day	Autumn potato	0.60	RMB/kg
Oxen labor	20.0	RMB/day	Summer potato	0.90	RMB/kg
Donkey labor	15.0	RMB/day	Flax	1.68	RMB/kg
–	–	–	Alfalfa	0.60	RMB/kg

[a] 1 US dollar = 6.3 RMB at year 2012.

revenue from natural capital, financial capital, and human capital. The mean of the input distance functions for all 2006 cropping systems is 1.742 (Table 5), which implies on average that the same amount of output can be produced by using only 57.4% (i.e. 1/1.742) of the observed inputs. This is the average of all systems evaluated rather than what farmers are actually using. In the case of soil, that means erosion could be reduced dramatically without reducing current production. Descriptive statistics of the inputs from the 2006 benchmark cropping systems are also given in Table 5. For example, the mean of soil loss for all 2006 benchmark systems is 1398 kg/ha, and it has a large range from 0 to 31,272 kg/ha. Mean nitrogen loss is 8.8 kg/ha, with a standard deviation of 5.9 kg/ha. The mean cost of labor is 839 RMB/ha.

4.2. Robustness of the DEA Benchmarks

To test the robustness of DEA benchmarks, we compared the results with those calculated by two of the benchmarks as suggested by Van Passel et al., yielding three potential benchmarks: 1) the DEA benchmark, 2) the average of all cropping systems, and 3) the first observed cropping system, characterized by mono-crop corn, non-mulching, contour, irrigation, human labor and no terracing. As demonstrated in Table 6, a Spearman's rank correlation of SE between different benchmarks reveals the correlation between the DEA and benchmark 2 to be 0.580; and the correlation to benchmark 3 to be 0.535. This implies that the ranking of the cropping systems is consistent across all three methods, thus supporting the robustness of the DEA benchmark.

4.3. Sustainable Value and Sustainable Efficiency

Descriptive statistics of SV and SE for all 2006 cropping systems are shown in Table 7. Since the best performing cropping systems are chosen as benchmarks, all SVs will be zero or negative. A SV of zero indicates that the cropping system uses all its resources in the most productive way. Large differences in SV of all 2006 cropping systems are observed, ranging from −4700 to 0 RMB/ha (−746 to 0 US dollars/ha). The SV of cropping systems can be improved by applying resources in a more productive way–i.e. moving towards the production frontier. The mean of SV is −1661 RMB/ha (−264 $US/ha); compared to the most sustainable cropping systems, the average cropping system loses 1661 RMB/ha (264 $US/ha) in SV.

The SE under DEA benchmarks is between 0 and 1. A SE of 1 indicates that the cropping systems are the most efficient from a sustainability perspective, while 0 implies the least efficient. The mean of the SE for

Table 5
Descriptive statistics of input distance functions and the benchmark inputs.

Variable	Mean	Standard deviation	Minimum	Maximum
Input distance function	1.742	0.540	1	4.733
Soil loss(kg/ha)	1398	3084	0	31,272
Nitrogen surplus(kg/ha)	8.8	5.9	0.014	54
Labor (RMB/ha)[a]	839	447	40	2034

[a] 1 US dollar = 6.3 RMB at year 2012.

Table 6
Correlation between the rankings of sustainable efficiency for all 2006 cropping systems.

	Benchmark 1[a]	Benchmark 2[a]	Benchmark 3[a]
Benchmark 1	1		
Benchmark 2	0.580[***]	1	
Benchmark 3	0.535[***]	0.865[***]	1

Note: [***] significant at 1%.
[a] Benchmark 1 = DEA benchmarks; Benchmark 2 = the average cropping system; Benchmark 3 = the first observed cropping system, characterized by mono-crop corn, non-mulching, contouring, irrigation, human labor and no terracing.

all cropping systems is 0.689; on average the SE can be improved by 31.1%.

The histograms shown in Figs. 1 and 2 indicate the distribution of the SVs and efficiency scores. Almost 100 systems were perfectly efficient (have an SE of 1.0) and over 170 were very efficient with an SE of 0.9 or more. About 140 systems had a near zero SV (meaning they are already as sustainable as the benchmark). The distribution of the SVs is skewed with a large left tail, while the SE has a smaller left tail. The larger left tail for SV shows the magnitude of sustainability losses for the least sustainable systems.

4.4. SV and SE Comparisons

Three SV matrices for rotation, terrace techniques and land units are created using the estimation results and shown in Tables 8, 9 and 10. These tables can be used to compare the SVs between any pair of rotation types, terracing techniques or land units. Several more detailed tables can be found in Hou (2012) for those interested. The SV matrix for the 17 cropping systems is given in Table 8. The rotation types in the first row serve as references. Each value represents a movement from the system on the horizontal axis to the system along the vertical axis. For example, SV is reduced by 465.52 RMB (73.9 US dollars) when switching from corn to wheat and improved by 441 RMB (70 US dollars) if moving from corn to the best system, which is the CSC (i.e. corn, soybean, corn) rotation. A3CM (i.e. alfalfa for 3 years, corn, millet) and FA5MC (i.e. flax, alfalfa for 5 years, millet, corn) rank second. The cropping systems with PWCM (potato, wheat, corn, millet) and FWPM (i.e. flax, wheat, potato, millet) create the lowest SV. Wheat is typically low compared to rotations.

The SV matrix for three terracing techniques (Table 9) implies that bench terracing contributes most to SV, followed by spaced terracing. The cropping systems with no terraces have the least SV when all other practices are held equal. Not surprisingly, based on the SV matrix for five types of land units (Table 10), a floodplain is efficient, while very steeply sloped land has the least value.

A similar set of SE matrices reinforces the same results, but is not shown here.

5. Discussion

One of the priorities of this study is to make practical recommendations for improving sustainable agricultural practices in China's Loess Plateau to balance economic and environmental objectives. SV is computed for different agricultural systems (crop types, land types and cropping techniques) and recorded and organized into comparison matrices. These comparison matrices can be used to compare the relative sustainability of different crops or management practices like rotations

Table 7
Descriptive statistics of sustainable value and efficiency for 2006 cropping systems.

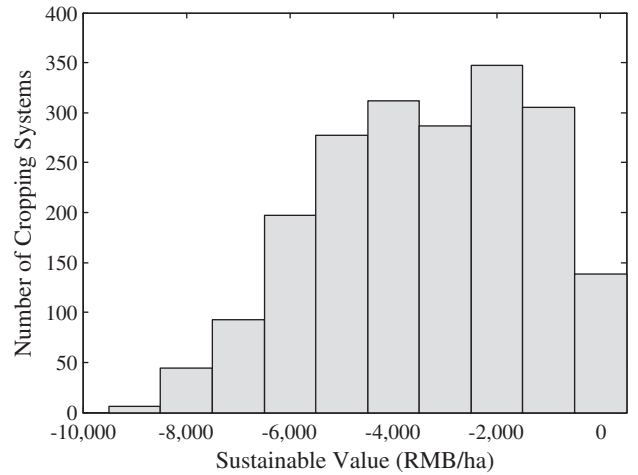|	Mean	Standard deviation	Minimum	Maximum
Sustainable value (RMB/ha)	−1661	1013	−4700	0
Sustainable efficiency	0.689	0.165	0.263	1

Fig. 1. Histogram of sustainable value for all cropping systems.

and terracing. For example, cropping systems with potatoes or wheat typically were less sustainable than systems with alfalfa and corn. A regression was also used to specify the marginal contribution of cropping system characteristics on SV or SE. Overall, the DEA/SV analysis of Lu et al.'s 2006 potential cropping systems for the region demonstrated that, all things held equal, bench terracing contributes the most to SV. SV is reduced by 465.52 RMB (73.9 US dollars) when switching from corn to wheat and improved by 441 RMB (70 US dollars) if moving from corn to the best system, which is the CSC (i.e. corn, soybean, corn) rotation.

On average, SV is −1661 RMB (−264 US dollars) and SE is 69%. Clearly, soil erosion could be reduced without sacrifices in income if producers switched to more efficient systems. However, these results are limited to the present data and the dimensions of sustainability that were considered. Income might be affected, for example, if a change in cropping systems leads to less diversity, and therefore more exposure to the risk of disease.

In contrast to other accounting approaches that make adjustments to GDP, the DEA/SV method can be used to inform policy makers, farmers, and farm managers about the sustainability of regional natural resource management decisions. However, a limitation in the analysis is that the sustainability values are based on simulation, rather than the sustainability of current agricultural practices (i.e. what farmers are currently using). Therefore, the results should be viewed in the context of potential, rather than actual, impacts.
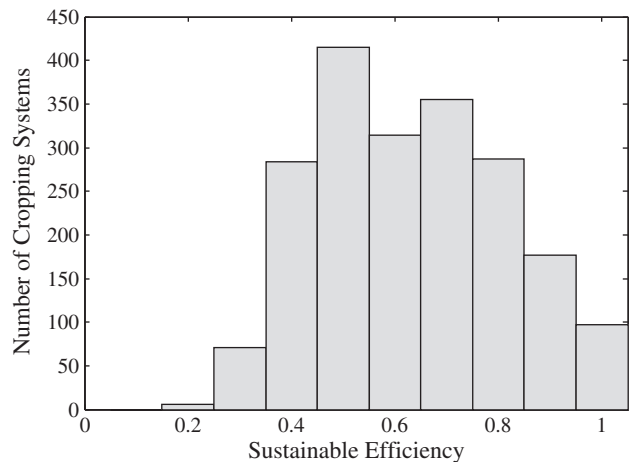

Fig. 2. Histogram of sustainable efficiency for all cropping systems.

Table 8
Sustainable value comparison matrix for 17 cropping rotations (RMB/ha)[a].

Cropping rotations[b]:	C	W	PWC	CMP	CSC	FWPM	PWCM	MSC	WPMCF	MSMP	A3CM	A3CPM	A3MPM	A4MPM	FA5MC	FWA4MC	A3MCPCM
C	0																
W	−465.52***	0															
PWC	−612.56***	−147.04**	0														
CMP	−966.38***	−500.86***	−353.82***	0													
CSC	441.16***	906.68***	1053.72***	1407.54***	0												
FWPM	−790.35***	−324.83***	−177.79***	176.03***	−1231.51***	0											
PWCM	−764.61***	−299.09***	−152.05**	201.77***	−1205.77***	0	0										
MSC	122.41***	587.93***	734.97***	1088.79***	−318.75***	912.76***	912.76***	0									
WPMCF	−839.53***	−374.01***	−226.97***	126.85*	−1280.69***	0	0	−912.76***	0								
MSMP	−459.81***	0	147.04*	500.86***	−906.68***	324.83***	324.83***	−587.93***	324.83***	0							
A3CM	293.44***	758.96***	906.00***	1259.82***	−147.72*	1083.79***	1083.79***	171.03***	1083.79***	758.96***	0						
A3CPM	0	465.52***	612.56***	966.38***	−441.16***	790.35***	790.35***	−122.41***	790.35***	465.52***	−293.44***	0.00					
A3MPM	0	465.52***	612.56***	966.38***	−441.16***	790.35***	790.35***	−122.41***	790.35***	465.52***	−293.44***	0.00	0				
A4MPM	0	465.52***	612.56***	966.38***	−441.16***	790.35***	790.35***	−122.41***	912.76***	587.93***	−171.03***	587.93***	0.00	0			
FA5MC	313.36***	778.88***	925.92***	1279.74***	−127.80*	1103.71***	1103.71***	190.95***	1103.71***	778.88***	0	293.44***	293.44***	293.44***	0		
FWA4MC	0	465.52***	612.56***	966.38***	−441.16***	790.35***	790.35***	0	912.76***	587.93***	−171.03***	0	0	0	−293.44***	0	
A3MCPCM	0	465.52***	612.56***	966.38***	−441.16***	790.35***	790.35***	−122.41*	790.35***	465.52***	−293.44***	0	0	0	−293.44***	0	0

0 = no significant difference; * = significantly different at 10% level; ** = significantly different at 5% level; *** = significantly different at 1% level.

[a] SV switching from the cropping rotation on the top to the cropping rotation on the side is negative if the switch is less sustainable and positive if more sustainable.

[b] A# = alfalfa and years, e.g. A3 = three years alfalfa; C = corn; M = millet; F = flax; P = potato; S = soybean; W = winter wheat.

Table 9
Sustainable value comparison matrix for 3 terracing techniques (RMB/ha)[a].

	No terracing	Bench terrace	Spaced terrace
No terracing	0		
Bench terrace	1178.5***	0	
Spaced terrace	122.5***	−1056***	0

0 = no significant difference; * = significantly different at 10% level;** = significantly different at 5% level;*** = significantly different at 1% level.

[a] SV switching from the terracing technique on the top to the terracing technique on the side is negative if the switch is less sustainable and positive if more sustainable.

The fragile ecosystem in the Loess Plateau is associated with environmental degradation. The region concerns environmentalists, ecologists, economists, agronomists and policy makers alike. As previously stated, much of the agricultural land in the region has already been converted to trees through the Grain for Green program (Feng et al., 2005). However, planting land to permanent forests is an extreme conservation measure that generates little economic return to farmers (Osmond et al., 2012). Perhaps excessive erosion has been traded in for excessive conservation. Policy makers need information and ways to compare systems if they aim to realize both strong economic and social performance with sustainable use of natural resources (Fan et al., 2005; Guobin, 1999; Wang et al., 2003). Combining the DEA with the SV metric allows for customizable benchmarks that can, at least in theory, facilitate a practical comparison between agricultural land management decisions.

This is due, in part, to the fact that this combined DEA/SV approach accounts for the depreciation of natural capital through soil erosion and nitrogen losses, along with human capital. Policy makers can consider tradeoffs between economic and environmental objectives, as well as extreme solutions that focus on just the environment or just economics. In this comparison of over 2000 possible cropping systems, switching from mono-crop corn to a corn–soybean–corn rotation would generate 441 RMB/ha in SV. When armed with this knowledge, Chinese policy makers can take steps to educate farmers about the benefits of these trade-offs. In poor areas of China, farmers may lack knowledge about advanced cropping practices. The government also can provide financial incentives to farmers to switch from unsustainable to sustainable cropping systems by subsidizing or offering technological support.

6. Conclusions

One of the major challenges in measuring sustainability is determining how to compare market (e.g. profit) and non-market (e.g. environmental degradation) impacts. This study finds that the SV approach can be used efficiently and effectively to investigate the sustainability of cropping systems and include multiple forms of capital. It is especially useful to create a method to monetize the depletion of soil and nitrogen natural capital so that tradeoffs could be compared to profit maximization of crops, while also accounting for other forms of capital.

Table 10
Sustainable value comparison matrix for 5 types of land units (RMB/ha)[a].

Land Type	Floodplain	Gently sloping	Moderately sloping	Steeply sloping	Vey steeply sloping
Floodplain	0				
Gently sloping	−496.7***	0			
Moderately sloping	−771.8***	−275.1***	0		
Steeply sloping	−908.1***	−411.4***	−136.3***	0	
Vey steeply sloping	−935.1***	−438.4***	−163.3***	−27.0***	0

0 = no significant difference; * = significantly different at 10% level;** = significantly different at 5% level;*** = significantly different at 1% level.

[a] SV switching from the land type on the top to the land type on the side is negative if the switch is less sustainable and positive if more sustainable.

The mean SV for over 2000 cropping systems in the Loess Plateau is −1661 RMB/ha (−$264/ha); SE is 69%. Therefore, the sustainable performance of available cropping systems in the Loess Plateau can be improved by 1661 RMB/ha, or about 30%, by allocating resources to the best systems as compared to average systems. This analysis developed comparison matrices to examine which practices contribute most to sustainability. Based on these matrices for all cropping rotations, the corn–soybean–corn rotation is most sustainable. Flax–wheat–potato–millet is the least efficient. Bench terracing generates the most SV and produces the highest SE. Not surprisingly, the SV with a floodplain is better than sloped lands. Cropping systems with crop mulching, furrow ridging and intensive mechanization are more sustainable than those with non-mulching, contouring and lower mechanization level, respectively. Finally, the machine intensive cropping system characterized by the rotation corn, soybean, corn, with mulching, furrows ridging, and bench terracing in a floodplain, has the highest SE.

In a broader context of the sustainability measurement literature, this study enhances the SV method by creating individual, customized benchmarks through the use of the DEA. This method proves robust for estimating SV and SE, while offering a customized individual benchmark for each of the 2006 cropping systems. In theory, adding the DEA facilitates a practical comparison between agricultural systems that lends to the identification of the most sustainable agricultural management practices. Although the example presented is based upon simulated data published by Lu (2000) and Lu et al. (2003), a combined DEA/SV approach could be used as an extension of Lu's body of work. A DEA/SV could be used to empirically assess changes in the actual agricultural practices of farmers in the Loess Plateau Region if land use data were collected. Should an empirical study prove successful, the customizable nature of the DEA benchmarks would allow the DEA/SV method to inform policy makers, farmers, and farm managers about the sustainability of cropping the region versus putting most of the farmland into trees as was done by the Green for Grain Program.

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