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Assurance Contracts to Support Multi-Unit Threshold Public Goods in Environmental Markets

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Abstract

The free riding incentive has been a major obstacle to establishing markets and payment incentives for environmental goods. The use of monetary incentives to induce private provision of public goods has gained increasing support to help market ecosystem services. Using a series of lab experiments, we explore new ways to raise money from individuals to support private provision of multi-unit threshold public goods. In our proposed mechanisms, individuals receive an assurance contract that offers qualified contributors an assurance payment as compensation in the event that total contributions fail to achieve the threshold provision cost. Contributors qualify by contracting to support provision with a minimum contribution. Evidence from lab experiments shows that the provision probability, group demand revelation, and social welfare significantly increase when the assurance contract is present. Coordination is improved by the assurance payment especially for agents with values above the assurance level, leading to significantly higher aggregate contributions. A medium level of assurance payment used on units with medium and high value-cost ratios is observed to induce the largest improvement on social surplus. Our approach contributes to the private provision of environmental and other types of public goods.

Keywords Assurance payments · Threshold public goods · Multiple units · Lab experiment · Ecosystem services

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1 Introduction

In the last 15–20 years, and particularly in the U.S. since the 2008 Farm Bill created the USDA Office of Environmental Markets, environmental policy development has increasingly focused on market-based approaches to the provision of ecosystem services (MEA 2005; Gómez-Baggethun et al. 2010). Historically, changes in ecosystem services often involved non-market goods, either related to negative or positive externalities, such as excess nutrients discharged to rivers by the point or non-point sources and public goods such as wildlife habitat enhanced or degraded by some agricultural practices. Social institutions and governments have addressed these externalities through command and control regulation, philanthropic or conservation efforts, government payment for ecosystem services (PES), and, increasingly, through market-based approaches such as regulatory-driven cap-and-trade systems (Ferraro 2008, 2011; Schomers and Matzdorf 2013) or auction approaches (Cason and Gangadharan 2004; Banerjee et al. 2015; Liu 2021). These market-based approaches provide the potential to unleash the cost efficiencies of market incentives to achieve desired environmental outcomes. However, cap-and-trade approaches generally establish a demand for, say, discharge permits by stimulating pollution-regulated parties (firms) to be compliance-buyers. These approaches do not primarily engage the general citizen, although unregulated individuals may voluntarily enter the markets.[1]

Our research contributes to understanding alternative mechanisms to support the private provision of public goods, including ecosystem services and other types of environmental benefits with public goods properties. While the willingness to pay (WTP) for nature's benefits constitutes a foundation for regulatory, PES, and philanthropic approaches, individuals may not reveal their maximum WTP for public goods due to free riding incentives. Our study addresses the demand side and follows a growing body of effort that strives to improve methods for capturing at least some share of a willingness to pay as revenues that may support the private provision of public goods from ecosystem services (Ferraro 2008; Banerjee et al. 2013; Swallow et al. 2018). In particular, we focus attention on mechanisms to fund threshold-level public goods, which draws on the literature from charitable giving and is especially motivated by the conservation of wildlife habitat that requires a minimum number of acres and hence a threshold cost for a meaningful protection.[2] Poe et al.

[1] For example, websites exist where individuals may buy carbon offsets for personal travel. The ecosystemmarketplace.com provides an overview of alternatives, and a Google inquiry uncovers numerous alternatives (e.g., https://www.terrapass.com).

[2] Our motivating example here is the provision of safe habitat for grassland nesting birds, particularly the bobolink (Swallow et al. 2018). In the northeast of U.S., bobolinks largely depend on working hayfields for habitat, the nesting season directly conflicts with the desirable harvest schedule for agricultural providers to capture the peak nutritional value of hay as feed for livestock. Bobolink populations have experienced steep declines and are attractive to even casual bird watchers due to their visibility over grasslands and their easily identifiable song. In focus groups and feedback from donors to The Bobolink Project (Swallow et al. 2018), many individuals identify these birds with rural or childhood and family experiences, which stimulate a willingness to pay. Conservation of nesting habitat requires that farms forego harvests of a minimum of 10-acre hayfields so that a provision point of funding is necessary to compensate farmers for a discrete increment in foregone harvesting of hay. Furthermore, the presence of multiple parcels of habitat challenges the traditional framework of one unit threshold public good provision and requires us to allow local residents to potentially contribute to multiple parcels which motivates our multi-unit setup.

(2002) and Rose et al. (2002) provide nice reviews of experimental economics evaluations of threshold-level public goods, for which a provider establishes a provision point defined as a minimum level of funding required to deliver a unit of the public good.

Since Bagnoli and Lipman (1989), provision point mechanisms (PPMs) have been well studied, and the money-back guarantee has been associated with increasing contributions relative to the baseline of a more open-ended solicitation for donations (Rondeau et al. 1999, 2005; Poe et al. 2002; Rose et al. 2002). Many of these studies have involved the provision of a single unit, but for a more market-like approach to evolve, we seek a method capable of delivering multiple units. Unfortunately, experimental work has shown that games with multiple units of the public good can yield a multiplicity of equilibria and realize an even lower percentage of social surplus (Bagnoli et al. 1992). While the money-back guarantee reduces the incentive to free ride, it does not necessarily lead to participation or donation consistent with individuals' marginal WTP. For the provision of a single unit, researchers have considered various forms of a rebate of any funds raised over the provision point (Marks and Croson 1998; Spencer et al. 2009; Li et al. 2016; Liu et al. 2016), showing that rebates also reduce incentives to free-ride or cheap-ride, leading to increases in the rate of provision.[3] Rebates eliminate the possibility that a provider retains surplus generated by the generosity of donations made over the provision point.

This literature has also shown, however, that the provision point, with or without rebates, cannot consistently eliminate free-rider or non-provision equilibria without strong equilibrium refinements (Bagnoli and Lipman 1989; Bagnoli et al. 1992), particularly in a multi-unit public good setting (Bagnoli et al. 1992). Of course, if the challenges were simple, the public goods problem would have already been settled through the use of, for example, incentive-compatible mechanisms; unfortunately, such mechanisms are usually not budget-balancing and sometimes too difficult for novices to grasp (Clarke 1971; Groves 1973; Ledyard 1995; Attiyeh 2000; Kawagoe and Mori 2001). Alternatively, some studies have evaluated the potential to use penalties for individuals identified as free-riders or cheap-riders (Falkinger et al. 2000; Masclet et al. 2003). Here, we examine an alternative approach that rewards individuals who commit to contributing to the provision of the public good.

We begin from Tabarrok (1998)'s concept of a dominant assurance contract (DAC) under which would-be donors, who agree to a fixed contribution, qualify to receive an assurance payment from the market-maker (or the provider of the good) in the event that fundraising fails to achieve the provision cost. For example, if an individual agrees to donate a pre-specified amount of $40 but the provision fails, the market-maker will issue an assurance payment (e.g., $40) in addition to refunding the $40 donations. Tabarrok (1998) shows that the assurance contact can eliminate the non-provision equilibria with binary contribution choices and contributing to the public good becomes a dominant strategy with complete information for a single-unit case. The key idea is to encourage commitments of higher contributions by offering a conditional compensation (an assurance payment). The assurance contract mechanism tries to achieve the efficient provision by rewarding committed donors instead of penalizing free or cheap riders. However, this novel idea has not attracted much attention until recently.

[3] Here, free-riding occurs when an individual expresses a positive Hicksian willingness to pay (WTP) for a good but does not contribute to provision (zero contribution), while cheap-riding implies this person contributes a non-zero amount to provision but their contribution falls well short of reflecting their Hicksian WTP, at least at the margin.

Zubrickas (2014) proposes a mechanism called PPM with refund bonus (RBM), in which there is no minimum contribution requirement and the refund bonus (the assurance) is proportional to individual contributions. However, experimental results from Cason and Zubrickas (2017) do not show strong supports that the refund bonus mechanism perform better than PPM in general. Cason and Zubrickas (2019) and Cason et al. (2021) extend RBM to a dynamic setting to allow contributions over continuous time until a fixed deadline aiming to resolve equilibrium coordination, and find the best improvements upon PPM when two independent goods are available and refund bonuses are restricted to early contributions. Li and Liu (2019) introduce a variant of DAC, the assurance payment mechanism (APM), which allows continuous contributions while keep the original fixed assurance payment to provide an anchor for contribution coordination. Specifically, in APM, a predetermined assurance payment *AP* will be given as a compensation to whoever contributes at or above *AP* when the group contributions are insufficient for provision. They find APM improves upon PPM significantly based on laboratory experiments.[4] The mixed experimental evidence of assurance payments suggests the role of an explicitly defined *AP* as a more effective coordination device should be further tested.

To investigate the efficacy of the assurance payment mechanism in a more challenging environment, this paper expands APM from a single unit to multi-unit public goods provision. So far the existing variants of DAC mainly focus on the single unit case. However, Bagnoli et al. (1992) find experimentally that the coordination becomes much more challenging in a setting with multiple units. Intuitively, the coordination complexity in a multi-unit case increases significantly not only with multiple units to coordinate contributions on but also with an additional dimension of how many units to provide. We view a multi-unit setup as a step toward a market that is open to many providers, i.e., many farms providing hayfields with a single market-maker (Swallow et al. 2018). Specifically, we adapt the uniform price (UP) rule in the the framework introduced by Liu and Swallow (2019) where an individual pays the same price for all the units provided and the price equals one's contribution to the last unit that the group can collectively provide. UP is found experimentally to outperform significantly the traditional pay-your-bids approach in the case of multiple units. We leverage the multi-unit setup under UP to test alternative treatments of APM by varying the assurance payment levels on different units and the number of units assured to identify a guideline potentially for an optimal assurance design.

We show theoretically that the assurance contract shrinks substantially the set of contribution profiles supporting both non-provision and provision equilibria in the multi-unit threshold public goods game, similar to the single unit case. Actually, APM could eliminate the set of non-provision equilibria in a quite general setup. We then experimentally test alternative assurance payment schemes in a more realistic environment.

Our experiment results show that assurance payments significantly improve upon the baseline treatment PPM without assurance in the multi-unit setup, using the criteria of the rate of provision, the revelation of the group's value, and the realized social surplus. The key insight is that assurance payments improve coordination by providing the assurance payment (*AP*) as a focal point for individual contributions, especially for agents with values above *AP*, leading to significantly higher aggregate contributions. Particularly in the multi-unit setup, the effectiveness of assurance payments depends on the value-cost ratio (the total group values divided by the cost) of the unit of the good to be provided and the level of *AP* relative to the range

[4] Cason et al. (2021) also study a slightly different version of APM (call fixed refund bonuses therein) in a dynamic setting and report findings that are similar to those in Li and Liu (2019).

of individual values. A medium level of *AP* used on units with medium and high value-cost ratios is observed to induce the largest improvement on social surplus with both positive consumers and provider surpluses.

Before the remainder of the paper presents the mechanisms and theoretical remarks, the experimental design and hypotheses, and the laboratory results, one note is appropriate regarding the potential that an assurance contract scheme may require outside funds to back-up the liability of making assurance payments. We view this need for outside funds as different than, but analogous to, the concept of challenge grants or matching funds already used by philanthropic institutions or some government-managed PES systems. Matching funds have produced mixed results about charitable giving, requiring a balance between stimulating participation and donation while offsetting effects of crowding-out donations partially or wholly for some individuals (List and Lucking-Reiley 2002; List 2011). We suggest that one can view the assurance payment fund as an alternative form of a challenge grant, whereby an interested patron offers to pay committed, would-be donors to pursue provision under specified criteria, while the patron's funds have incentivized the donors. From the perspective of government, the assurance payment fund could be identified as a form of subsidy that is only committed in the event private donations meet specified criteria.

2 The Mechanisms and Theoretical Remarks

Assume there are N individuals who are asked to support J units of a public good with a constant marginal (per unit) cost C through voluntary contributions. Each individual is indexed by $i \in \{1, \ldots, N\}$ and each unit of the public goods is indexed by $j \in \{1, \ldots, J\}$. Individuals are asked to contribute toward each unit of the public goods simultaneously. Let v_i^j and b_i^j be individual i's value and contribution toward unit j, respectively. The total contributions on unit j are $B^j = \sum_i b_i^j$.

2.1 Multi-unit Public Goods Provision Without Assurance Payments

The baseline mechanism is a uniform price (UP) mechanism in a multi-unit setting where an individual pays the same price for all units provided (Liu and Swallow 2019). In the UP mechanism, we compare the total contributions from all individuals on each unit with the unit cost of the public good, starting from unit 1. If individuals' total contributions to the first unit are greater than or equal to the cost of unit 1, we move on to the second unit, and so on. This process continues until the total contributions for a unit are less than the unit cost for the first time or all available units are provided. For example, if the total contributions on the first, second, and third units are all greater than the unit cost, but the total contributions on the fourth unit are less than the unit cost, then only the first three units will be provided. Thus, the market-clearing rule to provide g units in UP can be expressed as

$$g = \begin{cases} 0 \;\; if \;\; \sum_i b_i^1 < C \\ j \;\; if \;\; \sum_i b_i^m \geq C, \, \forall m \leq j \in \{1, \ldots, J-1\}, \, m \in \mathbb{N} \; and \, B^{j+1} < C, \\ J \;\; if \;\; \sum_i b_i^m \geq C, \, \forall m \leq J, \, m \in \mathbb{N}. \end{cases} \quad (1)$$

Note that, to provide g units, the total offer on each of the first g units must be at or above the cost of each unit.

A pricing rule determines how much each individual has to pay in total. In UP, an individual pays the same price for all the units provided, and the price equals one's contribution to the last unit the group can collectively provide. The pricing rule is given by

$$t_i = \begin{cases} 0 & if \quad g = 0 \\ g * b_i^g & if \quad g \in \{1, \dots, J\}. \end{cases} \tag{2}$$

Thus, the payoff function π_i for individual i with g units provided in UP is

$$\pi_i = \begin{cases} 0 & if \quad g = 0 \\ \sum_{m=1}^{g} v_i^m - t_i & if \quad g \in \{1, \dots, J\}. \end{cases} \tag{3}$$

Liu and Swallow (2019) find that the UP rule substantially increases the provision rate compared to the "pay-as-bid" approach, by 6.9%, 57.9%, and 50% for providing at least one, two, and three units, respectively, given the availability of six units. The cost saving potential in UP might increase with the number of units since the UP rule has advantages in encouraging provision at the first several units due to the reduced penalty for over-contribution as the paid price for each unit is determined by the last unit provided.

2.2 Assurance Payment Schemes

An assurance payment is a predetermined compensation to whoever contributes at or above a pre-specified minimum offer when the provision fails. For simplicity, the compensation of an assurance payment is set the same as the minimum offer in the current setup.[5] For example, assume the assurance payment is \$10 on the first unit. If the total group contributions are below the cost of the first unit, that is, nothing will be provided in this case, then whoever contributes \$10 or above on the first unit will receive an assurance payment of \$10, in addition to a full refund of their original contributions (i.e., with money-back guarantee). Those who contribute less than \$10 will only receive their refunds but no assurance payment.

The original assurance contract in Tabarrok (1998) includes a binary contribution choice and specifies the number of individuals required to accept the contract to provide the good. In this paper, we allow for continuous contributions in a multi-uinit threshold public good setting. Specifically, let AP^j denote the assurance payment for unit j, then the payoff function for individual i with g units provided is

$$\pi_i = \begin{cases} 0 & if\ b_i^1 < AP^1\ and\ g = 0; \\ AP^1 & if\ b_i^1 \geq AP^1\ and\ g = 0; \\ \sum_{m=1}^{g} v_i^m - t & if\ b_i^{g+1} < AP^{g+1}\ and\ g \in \{1, ..., J-1\}; \\ \sum_{m=1}^{g} v_i^m - t + AP^{g+1} & if\ b_i^{g+1} \geq AP^{g+1}\ and\ g \in \{1, ..., J-1\}; \\ \sum_{m=1}^{J} v_i^m - t & if\ g = J. \end{cases} \tag{4}$$

Note that the assurance payment applies if and only if one's contribution is at the minimum offer level or above on the first unit that fails to be provided.

[5] Note that the minimum contribution level in order to obtain the compensation in case of non-provision is the same as the compensation assurance level in our current setup, which significantly simplifies our discussion and experimental design as the first step. A more general setup where these two parameters are set differently is investigated in our companion paper An et al. (2020).

2.3 Theoretical Remarks

This subsection provides an equilibrium analysis of contribution incentives in a multi-unit setting with and without assurance payments, developed from Bagnoli and Lipman (1989), Tabarrok (1998), and Liu and Swallow (2019). We characterize the set of Nash equilibria with assurance payments under complete information.[6] Let v_i and b_i denote individual i's value and contribution, respectively. The provision and non-provision Nash equilibrium sets for one-unit without assurance payments (the provision point mechanism with $AP = 0$) are characterized by Bagnoli and Lipman (1989) as follows.

Proposition 1 (Provision equilibrium, Bagnoli and Lipman (1989)): *Any strategy profile* $\{b_i\}_{i\in\mathcal{I}}$ *s.t.* $\sum_i b_i = C$ *with* $b_i \le v_i$, *for all* $i \in \mathcal{I} \equiv \{1, \dots, N\}$ *is a pure-strategy Nash equilibrium under which the good is provided.*

Proposition 2 (Non-provision equilibrium, Bagnoli and Lipman (1989)): *Any strategy profile* $\{b_i\}_{i\in\mathcal{I}}$ *s.t.* $\sum_i b_i < C$ *and* $v_k + \sum_{i\neq k} b_i \le C$ *for all* $k \in \mathcal{I}$ *is a pure-strategy Nash equilibrium under which the good is not provided.*

Proposition 1 states that any contribution strategy profile is a Nash equilibrium where the group contributions exactly add up to the provision cost, and no one contributes above their values. Proposition 2 states that if group contributions are less than the cost, no one can fill the gap alone without contributing above her value in a non-provision equilibrium. Note that both of the provision and non-provision equilibrium sets include multiple equilibria (or a continuum of equilibria) and the non-provision equilibrium set is never empty. When there are multiple units of a public good, we have

Proposition 3 (Nash equilibrium in multi-unit UP, Liu and Swallow (2019)): *the strategy profile* $\{b_i^1, b_i^2, \dots, b_i^J\}$ *for all* $i \in \mathcal{I}$ *is a pure-strategy Nash equilibrium with j units provided if*

- (a) $\sum_i b_i^l \ge C, \forall l < j$, and $\sum_i b_i^j = C$,
- (b) $v_i^{j+1} + \mathcal{B}_{-i}^{j+1} \le C, \sum_i b_i^{j+1} < C, \forall i$,,
- (c) $v_i^j + \mathcal{B}_{-i}^j \ge C, \forall i$.

where $\mathcal{B}_{-i}^l \equiv l \sum_{k\neq i} b_k^l - (l-1) \sum_{k\neq i} b_k^{l-1}$.

Proposition 3 includes the conditions (b) and (c) which ensure that individual i cannot change bids to acquire a higher profit by providing one more or less unit, respectively.[7] In the following proposition we show that an assurance contract can change the equilibrium conditions due to the potential to receive an assurance payment. The Nash equilibrium set with assurance payments is characterized as follows.

[6] Complete information here means that the following information is common knowledge: the provision cost for each unit, the group size, and the value of each unit for each individual.

[7] Liu and Swallow (2019) provide a general condition where individuals cannot deviate from the provision by more than one unit. Here we assume that individuals cannot obtain a higher profit by deviating from the equilibrium outcome by one unit, while our framework in this paper can still be generalized to cases where deviating by more than one unit is allowed. The proof can be reconstructed easily from Proposition 4 below.

Proposition 4 (Nash equilibrium with assurance payments in multi-unit UP): *the strategy profile* $\{b_i^1, b_i^2, \ldots, b_i^J\}$ *for all* $i \in \mathcal{I}$ *is a pure-strategy Nash equilibrium with assurance payments in the range of* $[C/N, C]$ *on all units available if the following three conditions are satisfied when j units are provided*:[8]

- (a) $\sum_i b_i^l \geq C, \forall l < j$, *and* $\sum_i b_i^j = C$,
- (b) $v_i^{j+1} + \mathcal{B}_{-i}^{j+1} + \mathcal{A}^{j+1} \leq C, \sum_i b_i^{j+1} < C, \forall i$,
- (c) $v_i^j + \mathcal{B}_{-i}^j + \mathcal{A}^j \geq C, \forall i$.

where $\mathcal{B}_{-i}^l \equiv l \sum_{k \neq i} b_k^l - (l-1) \sum_{k \neq i} b_k^{l-1}$, $\mathcal{A}^l \equiv I(b_i^{l+1} \geq AP^{l+1})AP^{l+1} - I(b_i^l \geq AP^l)AP^l$.

Proof See "Appendix". □

Compared with Proposition 3, Proposition 4 shows that an assurance contract changes the equilibrium conditions through the potential to receive an assurance payment. Corollary 1 below shows that an assurance contract can eliminate a substantial subset of contribution profiles supporting non-provision equilibria compared with the baseline case where no assurance is available.

Corollary 1 *The assurance contract changes the upper bound and increases the lower bound of the group contribution on the first unit that cannot be provided in equilibrium compared to the no-assurance contract. Without assurance, a zero-group contribution on the first non-provided unit is always an equilibrium. With an assurance contract, the group contribution must be at or above* $C - AP^{j+1}$ *on unit* $(j+1)$ *in an equilibrium that provides j units, where* $j = 0, 1, \ldots, J-1$.

Proof See "Appendix". □

Corollary 1 shows that an assurance contract increases the lower bound of group contributions from 0 to at least $C - AP^{j+1}$ on unit $(j+1)$ given that j units are provided in equilibrium. In contrast, a zero-group contribution is always an equilibrium outcome when there is no assurance payment. When $AP = 0$, the bounds of group contributions under UP with and without assurance payments coincide. Therefore, the assurance payment provides strong incentives of contribution even in the case of non-provision.

Based on Corollary 1, we also have

Corollary 2 *For any value distribution on unit j with a group of N individuals and a provision cost C, if there exists a* $\bar{v}^j$ *such that* $C/\bar{v}^j \leq n^*$, *where* n^* *is the number of individuals with values greater than or equal to* $\bar{v}^j$, *then provision is the only equilibrium outcome with* $AP^j = \bar{v}^j$ *under a monotonic bidding function, where individuals' bids do not decrease with values*.[9]

[8] Here we assume the assurance payment $\geq C/N$ on each unit to avoid the trivial case in which everyone just contributes the assurance level but the good is not provided and everyone earns the assurance payment.

[9] A non-decreasing bidding function is generally obtained theoretically (Alboth et al. 2001; Laussel and Palfrey 2003) and observed experimentally (Li et al. 2016; Liu et al. 2016) for threshold public goods provision games.

Proof See "Appendix". □

Corollary 2 provides a condition where provision becomes the only equilibrium outcome on a certain unit. When $b_i^{j+1} \geq AP^{j+1}$ for any $v_i^{j+1} \geq AP^{j+1}$ in a non-provision equilibrium, $n^* \geq C/AP^{j+1}$ implies a group contribution not lower than *C*, contradicting the non-provision condition. As a result, for a given unit, we find that only provision equilibria exist when the number of individuals with values at or above *AP* is greater than *C*/*AP* based on Corollary 2.

In the next section, we design a series of assurance payment schemes and use lab experiments to investigate the effectiveness of assurance payments and explore the conditions for an optimal assurance contract.

3 Lab Experiments and Hypotheses

3.1 Experimental Design and Implementation

In the lab experiment, a maximum of 6 units of a public good are available for provision. Individuals' induced values for the public good follow a linear, decreasing marginal (per unit) benefit function. The induced values for unit 1 and unit 6 are randomly drawn from two uniform distributions over [15, 25] and [5, 15], respectively. The induced values for units 2 through 5 are interpolated linearly based on the realized values on units 1 and 6. The average cost for each unit is set as 10 per capita, and hence the provision cost for each unit in a group of size *N* is 10**N*. The value distribution, group size, and the provision cost for each unit are common knowledge.

To test the effects of various assurance payment schemes over multiple units, we designed the following six treatments: (1) the no assurance baseline, or the treatment *Base*; (2) the same assurance payment of 10 for the first three units only, or the treatment *P*10; (3) the same assurance payment of 14 for the first three units only, or the treatment *P*14; (4) decreasing assurance payments of 18, 14, and 10 for the first three units, respectively, or the treatment *PDe*; (5) the same assurance payment of 10 for all six units, or the treatment *C*10; (6) the same assurance payment of 14 for all six units, or the treatment *C*14. Treatments *P*10, *P*14, and *PDe* are partial assurance schemes, while *C*10 and *C*14 are conditional assurance schemes for all available units as all six units are potentially covered by the assurance payment up to the first unit that fails to be provided.

The treatment design is based on theoretical predictions as well as practical considerations. We choose three assurance payment levels of 18, 14, and 10 based on Corollary 2 where we demonstrate different payment levels have distinct impacts on the set of non-provision equilibria. In a multi-unit context, the number of units covered by assurance payments needs to be considered. Therefore, we test both the partial and conditional assurance payments where the first several and all units are assured, respectively.

We conducted two phases of lab experiments on networked computer terminals, with phase 1 including the partial assurance treatments and phase 2 including the conditional assurance treatments (Table 1).[10] The experiment was conducted with students from a

[10] We use a within-subject design, with four sessions of treatment sequences (*Base-P10-P14*, *P10-Base-PDe*, *P14-PDe-P10*, *PDe-P14-Base*) for phase 1 and two sessions of treatment sequences (*Base-C10-C14*, *Base-C14-C10*) for phase 2. That is, for phase 1, a treatment sequence consists of three of the four treatments of *Base*, *P*10, *P*14, and *PDe*, with each ordered in the first, second, and third once in one of the four treatment sequences, while for phase 2, sessions start with *Base* and rotate *C*14 and *C*10 as the second, leaving the other as the third. Each session has two groups of the same size.

major public university in the Northeast U.S. Each session has 10, 12, or 14 subjects in total, split evenly into two groups of 5 to 7, with a small variation due to subjects failing to show up. At the start of each treatment, the experimenter read the instructions aloud as subjects read along. At the end of the instruction and before decisions were made, quiz questions were given to assess subjects' understanding. Each treatment had 15 decision periods. In each period, subjects were randomly matched into one of the two groups to mimic the one-shot game environment and were assigned induced values for each unit as described above.[11] Then they submitted contributions to each unit in a decision period. At the end of each period, subjects were informed how many units were provided, their per-unit payment, earnings, and assurance payments if any.

At the end of a session, earnings were summed up over all periods. The average earnings were about $24 with an average time length of 75 minutes. Subjects were recruited through a university-wide daily digest email server and from an email list of students who expressed interests in participating in experiments. Our experiment dataset contains 3330 (=222*15) individual-period level decisions with 19,980 (=3330*6) individual-unit-period level observations. The software z-Tree (Fischbacher 2007) was used for the program.

Our experiment was designed to mimic the real-world scenarios where multiple units of a public good may need to be provided. We focus on the provision success rate and the group contribution-value ratio. We look at the provision success when the realized group total values are at or above the provision cost, in which case the provision rate for each unit measures the probability of an efficient decision being made. The group contribution-value ratio for each unit is the ratio of group total contributions to the realized group induced values, which represents the demand revelation and is an important measure for non-market valuation studies.

Given our experimental design, the value distribution is determined by the value range in a uniform distribution on a certain value interval, and its relationship with the unit cost C can be presented by the expected value-cost ratio (the expected group value divided by C). Table 2 shows the range and mean of induced values for each unit in the experiment. The expected value-cost ratios are 2, 1.8, 1.6, 1.4, 1.2, and 1 respectively for units 1 to 6 and are denoted as high for units 1 to 2, medium for units 3 to 4, and low for units 5 to 6. In our experiment, the randomization of group members and induced values in each period potentially increases the difficulty of coordination, which will provide a stronger test of differences among mechanisms and bring more variations to better identify the treatment effect. Furthermore, varying induced values may also enhance learning by encouraging subjects to think more carefully about the contribution strategy over a range of induced values instead of a specific contribution amount given a fixed induced value.

3.2 Experimental Hypotheses

We provide a set of testable hypotheses based on the experimental design and theoretical insights.[12] Corollary 1 suggests the following two hypotheses comparing assurance payment schemes with the baseline UP without assurance payments in general.

[11] See sample experimental instructions in "Appendix".

[12] The characterization of the equilibrium set for the multi-unit case with assurance payments in an information environment close to the real world is beyond the scope of this paper. Our lab experiments are designed to mimic some real-world scenarios and to provide insights on how assurance payments could improve the private provision of public goods.

Table 1 Experiment treatments and sessions

Assurance type	Treatment	No. of groups	No. of sessions	No. of subjects	Group size in each session
Partial assurance	*Base*	6	3	34	(5, 5, 7)
	P10	6	3	34	(5, 6, 6)
	P14	6	3	36	(5, 6, 7)
	PDe	6	3	38	(6, 6, 7)
Conditional assurance	*C10*	4	2	26	(7, 6)
	C14	4	2	26	(7, 6)

We test the following six treatments (1) No assurance baseline (*Base*); (2) a constant assurance payment of 10 for the first three units (*P*10); (3) a constant assurance payment of 14 for the first three units (*P*14); (4) decreasing assurance payments of 18, 14, and 10 for the first three units, respectively (*PDe*); (5) a constant assurance payment of 10 for the first unit that cannot be provided (*C*10); (6) a constant assurance payment of 14 for the first unit that cannot be provided (*C*14) in six sessions with treatment sequences of *Base-P10-P14*, *P10-Base-PDe*, *P14-PDe-P10*, *PDe-P14-Base*, *Base-C10-C14*, and *Base-C14-C10*, generating 6 and 4 groups of observations for each partial and conditional assurance treatment, respectively, given that each session has two groups of the same size

Hypothesis 1 Assurance payments improve the provision rate compared to the baseline when no assurance is available.

Hypothesis 2 Assurance payments increase group contributions compared to the baseline when no assurance is available.

The rationale for the first two hypotheses is that based on Corollary 1, assurance payments may facilitate group contributions that are very close to the provision cost, i.e., not lower than the provision cost by an assurance payment level, in contrast with the existence of the equilibrium outcome of a zero-group contribution when no assurance is available.

The comparisons among alternative assurance payment schemes depend on the level of the assurance payment. The minimum AP in our experiment is 10. We also use another two higher levels of $AP = 14$ and $AP = 18$. According to Table 2 and Corollary 2, the assurance payment level $AP = 10$ satisfies the condition under which non-provision equilibria are eliminated for the first three units ($C/10 = N$), while $AP = 14$ satisfies the provision-equilibria-only condition for the first two units (when $C/14 < N$) and mostly for the third unit.[13] When $AP = 18$, the assurance payment is relatively high and the number of individuals with induced values greater than 18 may be smaller than the minimum number to eliminate the non-provision equilibria when the value-cost ratio is low.[14] Therefore, based on Corollary 2, we propose the following hypothesis.

[13] In our experiment, the provision-only equilibria condition under $AP = 14$ is satisfied with 100%, 99%, and 80% of the realized group value profiles for data analysis for the first, second, and third unit, respectively.

[14] In our design, $AP = 18$ is only used for the first unit and the provision-only equilibria condition under $AP = 18$ is satisfied with 72% of the realized group value profiles for data analysis.

Table 2 Range and mean of the induced values for each unit

Unit	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
v_H	25	23	21	19	17	15
v_{Mean}	20	18	16	14	12	10
v_L	15	13	11	9	7	5

The variable names v_H, v_{Mean} and v_L represent the upper bound, mean, and lower bound of the induced values for the corresponding unit, respectively

Hypothesis 3 Among assurance payment schemes, the effects of assurance payments are the most significant for $AP = 10$ on the first three units and for $AP = 14$ on the first two units when there are only provision equilibria.

4 Experimental Results

We first use Fig. 1 to give an overview of group contribution-value ratio (i.e., group contributions divided by realized group induced values) in each period and five-period-moving-average provision rates, by *AP* and unit. In Fig. 1, grey lines represent session-specific group contribution-value ratios, dark black lines represent averages over sessions, green lines represent five-period moving average provision rates, and red lines indicate average cost-value ratios.[15] We use *U*1 to *U*6 to denote the number of unit (e.g., *U*2 represents unit 2). *AP*0, *AP*10, *AP*14, and *AP*18 denote the assurance payment levels of zero (no assurance payment), 10, 14, and 18, respectively.[16]

Figure 1 shows that with a relatively low cost-benefit ratio of 0.5 on unit 1, the group contribution-value ratio exceeded the cost-benefit ratio overall and unit 1 was provided approximately 80% of the time, which was higher with higher assurance payments although there seems not much difference between *AP*14 and *AP*18. When the cost-benefit ratio increases with the unit number due to decreasing per unit benefits, the group contribution-value ratio was close to the cost-benefit ratio on unit 2 and was exceeded on units 3 to 6, and the provision rate decreases over units. In general, the provision rates look higher under treatments with assurance compared to no assurance payment counterparts and a higher assurance payment seems to further increase the provision rate on units 2 to 5 with medium cost-benefit ratios.

Next, we compare the assurance payment schemes in terms of the provision rate and group contribution-value ratio in detailed analyses, and then discuss individual contribution behaviors. Lastly, we compare the assurance payment schemes according to the realized social surplus as well as the surpluses (or deficits) of consumers and the provider.

[15] Since the total group values vary with group size and the value realization and we are mainly interested in the effects of the level of *AP*, we use the ratio of group contributions to total realized group values, that is, the group contribution-value ratio, to normalize group contributions, and pool group contribution-value ratios based on the assurance payment level. The average ratio of provision cost to the realized group induced value pooling all treatments on each unit is used to provide a baseline comparable across *AP* levels.

[16] We have 36 group level observations in total on each unit in Fig. 1. Specifically, on unit 1, we have 10 observations for each of $AP = 0$, 10, and 14, and 6 for $AP = 18$. On unit 2, we have 10 for each of $AP = 0$ and 10, and 16 for $AP = 14$. On unit 3, we have 10 for each of $AP = 0$ and 14, and 16 for $AP = 10$. On units 4 to 6, we have 28 for $AP = 10$, and 4 for each of $AP = 10$ and 14.

4.1 Provision Success Rate for Each Unit

Figure 2 shows the provision rate for each unit by assurance payment scheme.[17] The provision rate decreases over units for all schemes from above 80% (unit 1) to 0 (unit 6) as the value-cost ratio decreases from 2 to 1, but varies with the assurance payment level on each unit. We have the following results to compare alternative assurance schemes in terms of provision rate. All the test statistics reported in this subsection are based on the test of proportions.

Result 1 Assurance payments improve the provision rate on units 1 to 5, where the value-cost ratios are greater than 1. All treatments fail to consistently deliver the socially optimal number of units.

Result 1 supports Hypothesis 1 in which the presence of an assurance payment improves provision rate compared to the no-assurance baseline. First note that the no-assurance treatment *Base* has the lowest provision rate over all units (the black line in Fig. 2), while the assurance payment $AP = 14$ generates the highest provision rate overall. Specifically, the treatment $P14$ has the highest provision rates of 0.95, 0.77, and 0.45 on the first three units, respectively. The treatment $C14$ has the highest provision rates of 0.13 and 0.05 on units 4 and 5, respectively. For the treatment *Base*, the provision rates are 0.80, 0.53, 0.13, and 0.01 for units 1 to 4, respectively, and 0 for the last two units. Depending on the realized induced values, providing 5 or 6 units is socially optimal. Our results show that all treatments fail to consistently deliver the optimal number of units. The treatment $C14$ has the highest provision rate of 5% of delivering 5 units while 6 units are never provided in the experiment.

When the value-cost ratios are relatively high (2 and 1.8) as on units 1 and 2, the medium and high assurance payments improve provision rate significantly. The treatments $P14$ and *PDe* have significantly higher provision rates than the *Base* treatment on the first two units (unit 1: 0.95 and 0.90 vs. 0.80, with $p = 0.0088$ and 0.0969; unit 2: 0.77 and 0.75 vs. 0.53 with $p = 0.0028$ and 0.0057), which is consistent with Hypothesis 3.

With a medium value-cost ratio of 1.6 on unit 3, provision rates under all the assurance payment treatments ($P10$, $P14$, *PDe*, $C10$ and $C14$) are significantly higher than that under the *Base* treatment (0.58, 0.77, 0.75, 0.58 and 0.58 vs. 0.53, all with $p < 0.01$). Conditional assurance treatments generate higher provision rates on units beyond those only partially assured. On unit 4, provision rates under the treatments $C10$ and $C14$ are significantly higher than *Base* both with $p = 0.0024$. On unit 5, $C14$ is significantly higher than *Base* with $p = 0.0265$.

Note that the treatments $P10$ and $C10$ are not statistically different from *Base* on units 1 and 2, indicating a drawback of a low *AP* on units with high value-cost ratios. When individual values are all higher than the unit cost per capita, the assurance payment $AP = 10$ imposes an upper bound of 10 on contributions for all individuals with values below 20 in a provision equilibrium, which limits the capacity of subjects with values above 10 but below 20 (i.e., relatively high-value people) to offset (compensate) the potentially lower

[17] When calculating the provision rate, we exclude the case in which it is not efficient to provide a unit given the total realized induced value. In our experiment data, the case of the total realized induced value being less than the cost happens only for units 5 (15 out of 720 observations, or 2.1%) and 6 (340 out of 720 observations, 47.2%).

individual contributions from those with values below 10.[18] For $AP = 14$ and 18, the upper bound is at least 14 or 18, and hence $P14$ and PDe improve provision rates on units 1 and 2 while $P10$ and $C10$ do not. Furthermore, $P14$ has a provision rate significantly higher than $P10$ on units 2 and 3 ($p = 0.0320$ and 0.0897), and PDe with $AP = 14$ on unit 2 is significantly higher than $P10$ on unit 2 ($p = 0.0528$); $P14$ has provision rates higher than $P10$ on unit 1 and PDe with $AP = 10$ on unit 3, although the differences are not statistically significant at the 10% level ($p = 0.1137$ and 0.1905).

We summarize the additional observations above in the following result.

Result 2 A medium or high assurance payment generally improves the provision rate compared to a low assurance payment. The effect of an assurance payment on the provision rate is the most significant at a medium level of value-cost ratio.

4.2 Group Contribution-Value Ratio for Each Unit

To understand the patterns of provision rates across assurance payment schemes, we further investigate the group contribution-value ratio for each unit. Figure 3 shows that a higher assurance payment generally induces a higher group contribution-value ratio and the same assurance level leads to similar group contribution-value ratios across treatments. The treatment PDe on unit 1 has the highest assurance payment of $AP = 18$, generating the highest group contribution-value ratio of 0.72. $P14$ on units 1 to 3, PDe on unit 2, and $C14$ on units 1 to 6 have the same assurance payment of $AP = 14$ and generate group contribution-value ratios around 0.62.

Similarly, $P10$ on units 1 to 3, PDe on unit 3, and $C10$ on all six units have $AP = 10$, resulting in group contribution-value ratios around 0.60. Under the treatment *Base* with $AP = 0$, the group contribution-value ratio decreases from 0.59 (unit 1) to 0.56 (unit 2), 0.52 (unit 3) and stays around 0.47 on units 4 to 6, all lower than the treatments with positive assurance payments. The pattern of group contribution-value ratio is consistent with the pattern of provision rate over units.

We run a two-factor (group and period-specific) random-effects regression of group contribution-value ratio on the assurance payment level and treatment dummies for each unit based on the data from the last 10 periods (Table 3).[19] The variable *Base* is the baseline treatment, $AP10$, $AP14$, and $AP18$ are dummy variables that represent different assurance payment levels. The conditional assurance schemes are treated as the baselines and the dummies for the partial assurance schemes are interacted with the assurance payment

[18] On units 1 and 2, the value-cost ratios are relatively high (2 and 1.8) with the lowest induced values of 15 and 13 on the first and second units, respectively. The unit cost per capita is 10.

[19] The two-factor random effects models are based on the following regression: $y_{it} = X_{it}\beta + \mu_i + v_i + \epsilon_{it}$, where y_{it} represents the group contribution-value ratio for group i in period t, with the two random effects denoted by μ_i and v_i, respectively, and X_{it} is a set of regressors including dummies for assurance payment levels and some interaction terms across treatments. The group contribution-value ratio of aggregating the two groups, that is, the ratio of the aggregated two-group contributions to the aggregated two-group induced values, is used in the regression to be consistent with the session-group specific effect, since group members are reshuffled among two groups in each period. We exclude the observations from the first five periods to avoid potential learning effects in the early periods. We have run the same model specifications using all 15 periods of data and results are very close.

dummies to identify the difference between conditional and partial assurance schemes.[20] Regressions results show that assurance payments induce higher contribution-value ratios, consistent with the results of provision rate. In "Appendix" Table 7, we further control for the group size and the results remain unchanged.

Result 3 Assurance payments significantly increase group contribution-value ratios on all units.

All assurance payment schemes lead to higher group contribution-value ratios on units 1 to 3 with a significance level of at least 0.01, except for $P10$ on unit 1. On units 4 to 5, $C10$ and $C14$ significantly increase the contribution-value ratios by about 12% to 19% compared to the *Base* treatment, both with $p < 0.01$. Result 3 is consistent with Hypothesis 2 that the presence of assurance payments improves the group contribution compared to the no-assurance baseline. We use the group contribution-value ratio to adjust for variations in the realized induced values.

Result 4 The differences in group contribution-value ratios are not statistically significant across assurance schemes with the same assurance payment level.

In Table 3, none of the interaction terms between assurance payment levels and assurance schemes are significantly different, except on units 4 to 6 when there is no assurance payment. Although the three partial assurance schemes $P10$, $P14$, and *PDe* have zero assurance payments on units 4 to 6, the resulting group contribution-value ratios are lower than those under *Base*, and the differences are significant for $P10$ on units 4 to 6 and $P14$ on unit 6, implying that the assurance payments on the first three units may discourage the contribution-value ratio on the non-assured units of 4 to 6.

Result 5 A higher assurance payment results in a higher group contribution-value ratio with high value-cost ratios on units 1 to 3. A lower assurance payment induces a higher group contribution-value ratio with low value-cost ratios on units 4 to 6.

The highest assurance payment $AP = 18$ generates a significantly higher group contribution-value ratio than $AP = 14$ and 10 both with $p < 0.01$ on unit 1. The assurance payment of $AP = 14$ generates group contribution-value ratios higher than that of $AP = 10$ on units 2 and 3, with $p = 0.054$ and $p = 0.164$, respectively. On units 4 to 6, however, the assurance payment of 10 induces higher group contribution-value ratios than $AP = 14$ with $p = 0.241$, 0.008, and 0.089, respectively.

[20] We use dummies of *AP10* and *AP14* to denote the conditional assurance schemes on all six units and they are respectively interacted with dummies of *P10* and *P14* for partial assurance on Units 1 to 3 (*AP10**P10* and *AP14**P14*) to distinguish the potential different effects from the partial and conditional assurance payments. Since the treatment *PDe* induces three different assurance payments of 18, 14, and 10 respectively for Units 1 to 3, a dummy *AP18* and the interaction terms of *AP14**PDe* and *AP10**PDe* are added respectively into regressions for Units 1 to 3. The treatment dummies *P10*, *P14*, *PDe* are included for Units 4 to 6 to distinguish the difference between the partial assurance and no assurance payment schemes, with the latter as the baseline. The specifications in Table 3 are designed to simplify the regression models and highlight the effects of assurance payment levels on the contribution-value ratio.

Table 3 Two-factor random effects models of group contribution-value ratio for each unit

Group con-val. ratio	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
AP10	0.0373*	0.0332**	0.0696***	0.167***	0.179***	0.189***
	(0.0197)	(0.0169)	(0.0159)	(0.0213)	(0.0205)	(0.0242)
AP10*P10	−0.0244	0.000917	−0.00725			
	(0.0251)	(0.0214)	(0.0204)			
AP14	0.0638***	0.0673***	0.0925***	0.141***	0.123***	0.147***
	(0.0197)	(0.0169)	(0.0159)	(0.0213)	(0.0205)	(0.0242)
AP14*P14	−0.0331	0.0103	0.022			
	(0.0251)	(0.0214)	(0.0204)			
AP18	0.137***					
	(0.0171)					
AP14*PDe		0.0214				
		(0.0214)				
AP10*PDe			−0.00828			
			(0.0204)			
P10				−0.0321*	−0.0616***	−0.0826***
				(0.0185)	(0.0178)	(0.021)
P14				−0.0144	−0.0205	−0.0426**
				(0.0185)	(0.0178)	(0.021)
PDe				−0.00104	−0.0115	−0.0189
				(0.0185)	(0.0178)	(0.021)
Constant (*Base*)	0.587***	0.550***	0.512***	0.452***	0.444***	0.444***
	(0.0178)	(0.0143)	(0.0151)	(0.026)	(0.0274)	(0.0283)
Log-likelihood	−228.1	−255	−268.2	−216.7	−224.1	−194.3
Number of observations	180	180	180	180	180	180
Number of periods	10	10	10	10	10	10

Standard errors in parentheses; $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$; *AP10*, *AP14* and *AP18* denote dummies for assurance payments of 10, 14 and 18, respectively; *P*10, *P*14, and *PDe* are the assurance scheme dummies. Specifically, we use dummies of *AP10* and *AP14* to denote the conditional assurance schemes on all six units and they are respectively interacted with dummies of *P10* and *P14* for partial assurance on Units 1 to 3 (*AP10*P10* and *AP14*P14*) to distinguish the potential different effects from the partial and conditional assurance payments. Since the treatment *PDe* induces three different assurance payments of 18, 14, and 10 respectively for Units 1 to 3, a dummy *AP18* and the interaction terms of *AP14*PDe* and *AP10*PDe* are added respectively into regressions for Units 1 to 3. The treatment dummies *P10*, *P14*, *PDe* are included for Units 4 to 6 to distinguish the difference between the partial assurance and no assurance payment schemes, with the latter as the baseline. The specifications here are designed to simplify the regression models and highlight the effects of assurance payment levels on the contribution-value ratio

Note that the relative magnitude of variables *AP*10 and *AP*14 switches for units 1 to 3 and units 4 to 6 in Table 3. *AP*14 is higher on units 1 to 3, while *AP*10 is higher on units 4 to 6.The switch reinforces our theoretical insights on how the effects of *AP* vary with the value-cost ratio, as demonstrated similarly in Result 2. The value-cost ratios are relatively high on units 1 to 3, and the effect of *AP* on the upper bound of individual contributions in a provision equilibrium is more significant. When $AP = 10$, the upper bound equals 10 for individuals with values between 10 and 20, and for $AP = 14$, the upper bound is 14 for values below 28. As a result, *C*14 with $AP = 14$ generally induces higher group contribution-value ratios than $C10$ with $AP = 10$ on units 1 to 3. For units 4 to 6 with low value-cost ratios, the lower bound ($C - AP$) of group contributions in a non-provision equilibrium plays a more prominent role, and a lower AP may induce relatively higher group contribution-value ratios.

4.3 Coordination of Contributions by Assurance Payments

The results of provision rate and group contribution-value ratio consistently show that assurance payments significantly improve upon the baseline treatment without assurance and the effects of the assurance do vary with the level of AP. We next investigate the mechanisms focusing on individual contributions pooled by the level of AP based on the following two observations. First, we note that group contributions rarely add up exactly to the unit cost. The percentage of group contributions being equal to the unit cost is the highest under $AP = 10$ on unit 3 with only 5.5%, followed by 3.1% under $AP = 14$ on unit 2.[21] This observation suggests that perfect group coordinations on the provision costs are rarely observed in the heterogeneous induced value environment. Thus, we focus on the the coordination of contributions at the individual level. Second, Result 4 shows that group contribution-value ratios are not significantly different across assurance treatment schemes with the same AP level. In Table 4, we find similar results based on individual contributions for each unit where the same AP induces similar individual contributions across different assurance schemes after controlling for the induced value. Therefore, we pool the data of individual contributions based on AP in the following analyses.

Result 6 Assurance payments increase the percentage of individual contributions at or above the equal-cost-share level and induce AP as a focal point, especially when individual values are at or above AP.

All assurance payments significantly increase the percentage of individual contributions at or above the equal-cost-share of 10. Figure 4 shows the cumulative distribution of individual contributions by assurance payment levels, pooling observations on all six units.[22] When $AP = 0$, 33.8% of individual contributions are weakly higher than 10, while the percent increases to 73.5%, 62.6%, and 82.6% for $AP = 10$, 14, and 18, respectively. Furthermore, all assurance payments induce AP as the focal point of individual contributions. The modes are 10 (47.3%), 14 (35.2%), and 18 (39.7%) for $AP = 10$, 14, and 18, respectively. The equal-cost-share level of 10 is the mode (16.6%) when there is no assurance payment, while $AP = 10$ induces 47.3% of contributions at the mode of 10. The pairwise comparisons among the four distributions are all significantly different with $p < 0.01$ based on the Kolmogorov-Smirnov tests with permutations.

We next use the frequency-weighted observed individual contributions at each induced value by the level of assurance payments to identify the driving factors of the coordination

[21] See Table 6 in "Appendix" for the percentages of group contributions being equal to the unit cost under each assurance payment level on each unit.

[22] The cumulative probability curve of $AP = 10$ uses the data of $P10$ on units 1 to 3 and $C10$ on all six units; similarly, the curve of AP=14 uses $P14$ on units 1 to 3 and $C14$ on all six units. The curve of $AP = 18$ uses PDe on unit 1, and all the other observations are used for the curve of $AP = 0$.

(Fig. 5).[23] Assurance payments induce contributions from individuals with values at or above *AP* to concentrate more on *AP*, as shown in panels (b) to (d) in Fig. 5. Under $AP = 0$, however, contributions are mostly below medium and hight assurance payment levels which are indicated by the green and purple dash lines in panel (a) and the percentages of zero-contributions are relatively large. When $AP = 10$, the percentage of contributions at 10 is 48.4%, while only 19.4% under $AP = 0$, for individuals who have values at or above 10. Similarly, the percentages of contributions at 14 and 18 are 39.3% and 47.7% for $AP = 14$ and 18, respectively, while only 0.50% and 3.4% under $AP = 0$, for individuals who have values at or above 14 and 18, respectively.[24] The differences above are all statistically significant with $p < 0.001$ by proportion tests, ranksum tests, and random effects probit regressions.

Figures 6 and 7 demonstrate the aggregate effects of the coordination on the assurance payments by plotting the mean and median of individual contributions against the induced values (rounded to the nearest integers). The mean or median contributions under the assurance payment levels of 0, 10, 14 and 18 are denoted by connected black, red, green, and purple lines, respectively.[25] Assurance payments induce higher individual contributions over all values (Fig. 6).[26] $AP = 18$ leads to the highest contributions among high induced values of 15 to 25. Under $AP = 10$ and 14, contributions are higher than $AP = 0$ over the low and medium value range of 5 to 18. Specifically, the contributions under $AP = 10$ are higher than those under $AP = 0$ and 14 in the low value range of 5 to 12, and the contributions under $AP = 14$ are higher than those under $AP = 0$ and 10 for the values of 14 and above.

Results above demonstrate the effect of the incentive created by assurance payments. Individuals with values above *AP* are more likely to contribute at least *AP*, leading to a higher average contribution for those with values above *AP*. This effect is the most significant for those with values just around *AP* where we observe the largest contribution increase. Figure 7 shows that the median contribution jumps up when the induced value reaches to the assurance payment level at $AP = 10$, 14, and 18. We summarize this result as follows.

Result 7 Assurance payments induce higher individual contributions for values at or above the assurance payment level, and the effect is the most significant for those with values just around *AP*.

[23] In Fig. 5, the horizontal axis denotes the induced values, the vertical axis denotes the observed individual contributions. Both of induced values and contributions are rounded to the nearest integers for easier comparisons. The size of the circles is proportional to the frequency of the contributions. The colored solid horizontal lines in panels (b) to (d) denote the corresponding assurance payment levels in the experiment.

[24] We observe similar patterns for the percentage of individual contributions at or above *AP* conditional on values strictly above *AP*. For $AP = 10, 14, 18$, the percentages are 76.5%, 59.7% and 65.0% at or above 10, 14 and 18, respectively, while 40.5%, 19.1%, and 14.3% under $AP = 0$.

[25] Since the assurance payment level of 18 is used only on unit 1, contributions under $AP = 18$ can be only observed in the value range of 15 to 25. Contributions under other assurance payment levels can be observed in the full value range of 5 to 25.

[26] We also run three random effects tobit regressions of individual contributions on treatment dummies to compare PPM and the assurance payment treatments with $AP = 10, 14, 18$, respectively. See Table 8 in "Appendix". The baseline is PPM in all three models. We use an indicator variable to reflect whether the value is greater than or equal to the assurance payment level *AP* and a dummy of *AP* to denote the treatment with the assurance payment level of *AP*. We also include an interaction term of the two dummies. We find the assurance payment treatments with $AP = 10, 14, 18$ all have intercepts significantly higher than PPM with $p = 0.022, 0.002, 0.010$, respectively. We observe a significant jump of the intercept coefficient for the value range of 14 and above ($p < 0.001$) under the treatment with $AP = 14$.

Table 4 Two-factor random effects models based on individual contribution for each unit

Ind. Con.	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
AP10	4.257*	2.783	2.011	4.383***	0.693	1.895**
	(2.262)	(2.114)	(1.968)	(1.675)	(1.161)	(0.789)
AP10**P*10	−2.639	−3.539	0.0302			
	(2.527)	(2.349)	(2.182)			
AP14	5.228**	4.995**	−1.868	−0.348	−1.214	1.079
	(2.181)	(2.078)	(1.986)	(1.73)	(1.202)	(0.813)
AP14**P*14	−2.08	−1.851	7.828***			
	(2.47)	(2.339)	(2.213)			
AP18	4.759**					
	(2.027)					
AP14**PDe*		0.915				
		(2.317)				
AP10**PDe*			4.283*			
			(2.198)			
*P*10				−2.034	−1.534	−1.460*
				(1.548)	(1.09)	(0.748)
*P*14				0.766	0.194	−0.0136
				(1.536)	(1.055)	(0.71)
PDe				0.266	1.237	0.377
				(0.189)	(0.938)	(0.288)
Value	0.470***	0.457***	0.450***	0.310***	0.346***	0.338***
	(0.0604)	(0.0637)	(0.0677)	(0.0661)	(0.0527)	(0.0413)
Value*AP10	−0.179	−0.126	−0.0578	−0.152	0.124	0.00594
	(0.112)	(0.117)	(0.123)	(0.119)	(0.0952)	(0.0752)
Value*AP10**P*10	0.123	0.211	−0.00279			
	(0.125)	(0.129)	(0.135)			
Value*AP14	−0.202*	−0.213*	0.214*	0.171	0.233**	0.0613
	(0.108)	(0.115)	(0.123)	(0.122)	(0.0971)	(0.0758)
Value*AP14**P*14	0.0865	0.126	−0.466***			
	(0.122)	(0.129)	(0.137)			
Value*AP18	−0.0896					
	(0.1)					
Value*AP14**PDe*		−0.0191				
		(0.128)				
Value*AP10**PDe*			−0.254*			
			(0.137)			
Value**P*10				0.118	0.0696	0.068
				(0.108)	(0.0878)	(0.0699)
Value**P*14				−0.0625	−0.0343	−0.0369
				(0.109)	(0.0861)	(0.0675)
Value**PDe*				−0.0125	−0.11	−0.0525
				(0.109)	(0.0867)	(0.0677)
Provision Cost	0.0529	0.0339	−0.00683	−0.00704	−0.0189	−0.0185
	(0.0681)	(0.0589)	(0.051)	(0.0555)	(0.0516)	(0.0473)

Table 4 (continued)

Ind. Con.	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
Constant (*Base*)	−1.073	−0.508	1.363	2.358	2.298	2.132
	(4.458)	(3.885)	(3.386)	(3.609)	(3.304)	(3)
Log-likelihood	−6526.72	−6291.66	−6199.08	−6106.82	−6008.39	−6036.19
Number of observations	2200	2200	2200	2200	2200	2200
Number of periods	10	10	10	10	10	10

Standard errors in parentheses; ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$; AP10, AP14 and AP18 denote dummies for assurance payments of 10, 14 and 18, respectively; *P*10, *P*14, and *PDe* are the assurance scheme dummies

4.4 Social Efficiency and the Optimal Assurance Payment Scheme

Our results support that assurance payments significantly increase provision rates and group contribution-value ratios. However, if a provision fails, the provider may incur a deficit due to the assurance payments. Although the payments are simply a surplus transfer from the provider to consumers from a societal perspective, this transfer could be costly to the provider and inconvenient in reality. Thus, we compare the realized social surplus across treatments and explore factors related to an optimal assurance payment scheme for multi-unit threshold public goods provision.

Table 5 presents the realized social surplus and its allocation between consumers and the provider. The potential maximum social surplus equals the sum of the realized induced values of all units minus the total provision cost and is normalized to 100 to provide the same benchmark across different treatments. The realized social surplus equals the sum of values on each unit provided minus the total cost for providing these units. The consumer surplus equals the sum of values on each unit provided minus their contributions, plus assurance payments if any. The provider surplus equals consumers' contributions minus the provision cost and assurance payments, or equivalently, the realized social surplus minus the consumer surplus.

Result 8 All assurance schemes improve the realized social surplus compared to the *Base* treatment, attributed to the significantly increased consumer surplus. The treatment *P*14 has the highest realized social surplus with both positive consumer and provider surpluses.

Table 5 shows that assurance treatments induce higher realized consumer surpluses than *Base*, which are all significant at $p < 0.001$ by rank-sum test. The conditional scheme *C*10 (with an assurance payment of 10) results in the highest consumer surplus 70 compared to 39 in the treatment *Base*. The *Base* treatment has the highest realized provider surplus, which is significantly higher than those in assurance payment treatments with $p < 0.001$. It is worth noting that the provider maintains a positive surplus in *P*14, indicating that *P*14 achieves a balanced budget in our experiment from the provider's perspective. All assurance treatments have higher realized social surpluses than the *Base* treatment, among which *P*14, *PDe*, and *C*10 are significantly higher with $p < 0.001$, $p = 0.0069$ and $p = 0.092$, respectively. The treatment *P*14 generates the highest realized social surplus with both positive consumer and provider surpluses. However, no treatment reaches a realized social surplus greater than 65% of the efficient surplus level, suggesting large improvement potentials for alternative rules for multi-unit public goods.

Therefore, $P14$ stands out as the "best" assurance payment scheme based on our experimental data, implying that a budget-balancing assurance scheme is potentially possible. Below we provide justifications regarding the effectiveness of the treatment $P14$.

First, our results suggest that medium and high assurance payments induce higher provision rates and group contribution-value ratios under high value-cost ratios. When the value-cost ratio is relatively high, a provision outcome is more likely to occur and the effect of AP on the upper bound of individual contributions in provision equilibria may be more significant. These effects can be shown by comparing $AP = 10$ with $AP = 14$. For example, Fig. 7 shows that under $AP = 14$ the median of individual contributions for values above 14 is 14, while under $AP = 10$ the median for values above 10 is mostly 10, indicating that there would be more contributions at or above a higher assurance payment level under a higher AP. The aggregate effect is demonstrated in panel (a) of Fig. 8 which shows the cumulative distribution of group contributions normalized by the group size N under $AP = 10$ and 14 on each unit.[27] In panel (a) with high value-cost ratios (2 to 1.6), $AP = 14$ induces the percentages of contributions above the threshold cost larger than $AP = 10$, indicating a better performance of a higher assurance payment under a relatively high value-cost ratio.[28]

Second, when the value-cost ratio is low, there are not many high values and the role of the lower bound $(C - AP)$ of group contributions in non-provision equilibria becomes more important, implying that the group contributions become lower but still closer to the provision cost, and hence a relatively higher group contribution-value ratio. In Fig. 8b with low value-cost ratios (1.4 to 1), the percentages of contributions greater than the cost are much smaller for both $AP = 10$ and 14, but $AP = 10$ induces distributions of contributions narrower and closer to the threshold cost than $AP = 14$, i.e., a smaller variance, indicating a relatively higher group contribution-value ratio of a lower assurance payment under a low value-cost ratio.[29] However, with a relatively low provision rate, a higher group contribution-value ratio (and contribution) may imply a potentially larger producer deficit.[30]

Third, when the value-cost ratio is very high (unit 1) or very low (unit 6), the role of AP is moderate, since it is either too easy or too difficult to provide the public good with or

[27] Panel (a) is for units 1 to 3 and panel (b) for units 4 to 6, representing high and low value-cost ratios, respectively. The vertical grey line at 10 represents the group-size normalized unit cost.

[28] In panel (a), the CDFs of $AP = 14$ (the green ones) are all below those of $AP = 10$ (the red ones), and the lower the intercept of a CDF and the vertical unit cost line, the larger the percentage of contributions above the threshold cost. By Kolmogorov-Smirnov tests with permutations, the differences of CDFs between $AP = 14$ and 10 on units 1 to 3 are at the significance levels of 0.221, 0.011, and 0.023, respectively.

[29] The contribution variance under AP=10 is significantly less than that under $AP = 14$ on units 4 to 6. By variance ratio tests, the p-values for the comparisons that $AP = 10$ induces a smaller variance than $AP = 14$ are 0.0749, 0.0009, and 0.0338 for units 4 to 6, respectively. By Kolmogorov-Smirnov tests with permutations, the differences of CDFs between $AP = 14$ and 10 on units 4 to 6 are at the significance levels of 0.392, 0.081, and 0.862, respectively.

[30] For example, the percentages (probability) of the assurance payments being paid in case of provision failure are sharply different under $AP = 10$ and 14, on average around 67% for the former while only 38% for the latter.

Table 5 Realized average social surplus and allocation

Treatment	Potential maximum Social surplus	Realized Consumer surplus	Realized Provider surplus	Realized Social surplus
Base	100	39	5	44
*P*10	100	61	− 11	50
*P*14	100	62	1	63
PDe	100	64	− 6	58
*C*10	100	70	− 17	53
*C*14	100	60	− 8	52

The maximum social surplus is normalized to 100 across treatments. The Realized Social Surplus equals the sum of Realized Consumer Surplus and Realized Provider Surplus. The Realized Provider Surplus can be negative with assurance payments when the provider makes payments to consumers upon provision failure

without the assurance payment.[31] When the value-cost ratio is at the medium level (unit 3), the effects of assurance payments on the upper and lower bounds of contributions are balanced and moderate, and the role of *AP* becomes the most significant.

To summarize, when the value-cost ratio is medium or high, a medium or high assurance payment could be used to increase the provision rate. A medium level of assurance payment is preferred to possibly achieve a balanced budget. When the value-cost ratio is low, no assurance payments should be used since assurance payments may occur and potentially lead to a large producer deficit.

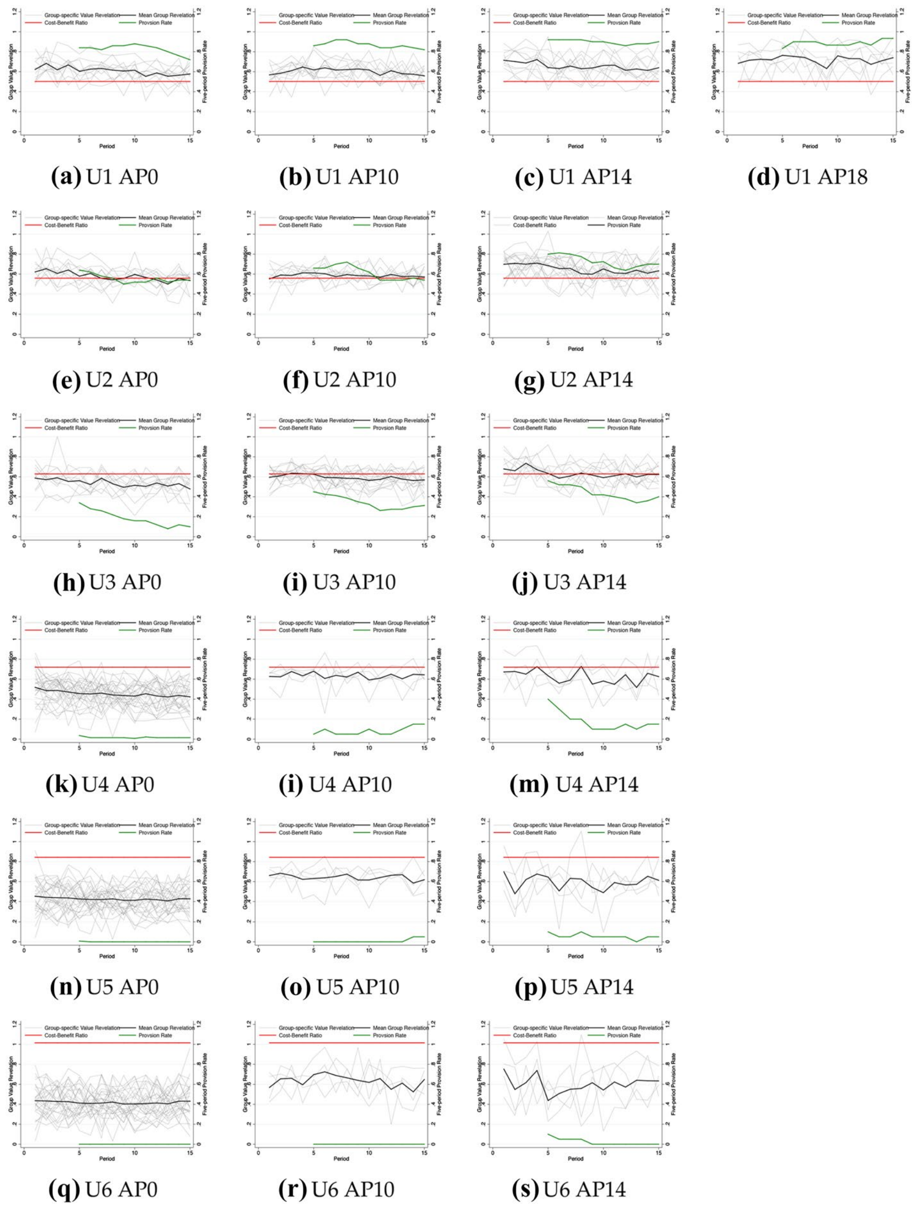
Result 9 In an optimal assurance payment scheme for multi-unit threshold public goods provision, a medium level of assurance payment should be used on units with medium or high value-cost ratios.

5 Conclusions

We address the need to develop mechanisms that encourage voluntary private contributions to support public goods provision. We build on the assurance contract introduced by Tabarrok (1998) and Li and Liu (2019) and generalize it to the multi-unit threshold public good provision framework in Liu and Swallow (2019). Under this approach, a market maker rewards a would-be donor for committing to a minimum contribution. If a provision fails, the market maker pays the committed donor an assurance payment as a reward, in addition to refunding their contribution under the scheme of money-back guarantee.

We seek to establish whether an assurance payment generally makes a significant improvement on the public good provision. We characterize the Nash equilibria with assurance payments and compare them with those without assurance payments ("Appendix" A). We then design six assurance payment schemes including the baseline and experimentally test the effects of assurance payments on the provision rate, group contribution-value ratio, and social efficiency. Our laboratory experiments show

[31] See Fig. 9 in "Appendix" for the cumulative distribution of group contributions normalized by the group size *N* for different assurance payment levels on each unit.



(a) U1 AP0 (b) U1 AP10 (c) U1 AP14 (d) U1 AP18

(e) U2 AP0 (f) U2 AP10 (g) U2 AP14

(h) U3 AP0 (i) U3 AP10 (j) U3 AP14

(k) U4 AP0 (i) U4 AP10 (m) U4 AP14

(n) U5 AP0 (o) U5 AP10 (p) U5 AP14

(q) U6 AP0 (r) U6 AP10 (s) U6 AP14

Fig. 1 Group contribution-value ratio in each period and five-period moving average provision rate by *AP* and unit. Panels above show the group contribution-value ratio in each period and five-period-moving-average provision rates, by *AP* and unit. Grey lines represent session-specific group contribution-value ratios, dark black lines represent averages over sessions, green lines represent five-period moving average provision rates, and red lines indicate average cost-value ratios

the assurance payment works in the expected direction, improving the prospect for real fundraising activities.

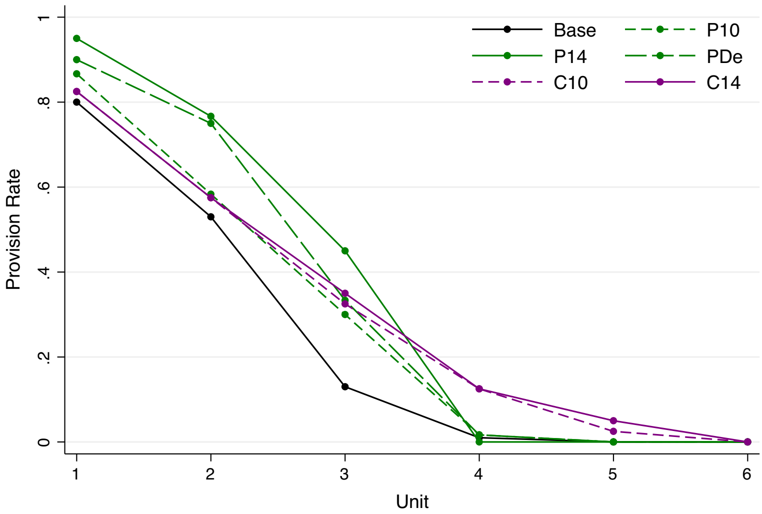


Fig. 2 Provision rate for each unit by assurance scheme. The figure shows the provision rates of the six assurance payment schemes, including the baseline treatment *Base* where no assurance payment is applicable for any unit

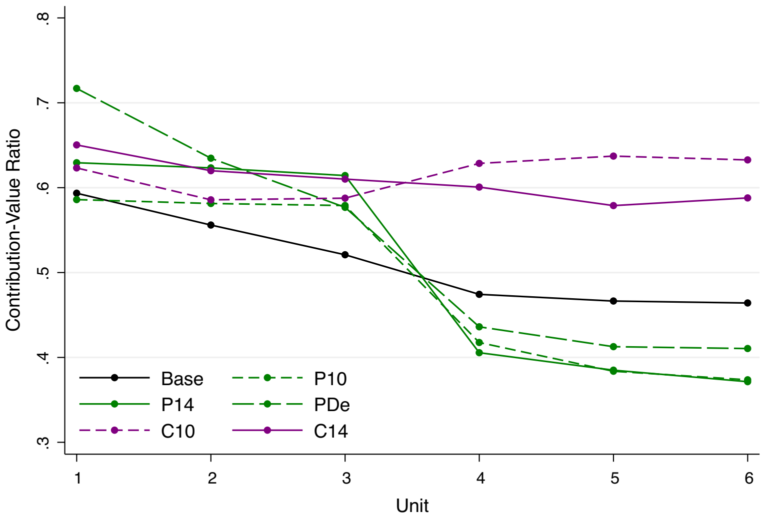


Fig. 3 Group contribution-value ratio for each unit by assurance scheme. The figure shows the group contribution-value ratios (group contributions divided by realized group induced values) in the six assurance payment schemes, including the treatment *Base* where no assurance payment is applicable for any unit

We find a well designed assurance payment always performs better than no assurance payment in terms of the provision rate, group contribution-value ratio, and realized social surplus. The key reason is that assurance payments improve the coordination of individual contributions by providing *AP* as a focal point, especially for those with values above the assurance payment level, and as a result increase the percentage of individual

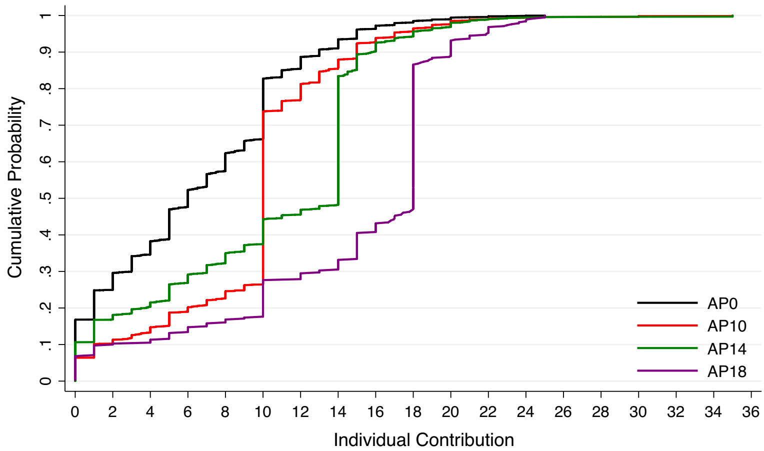
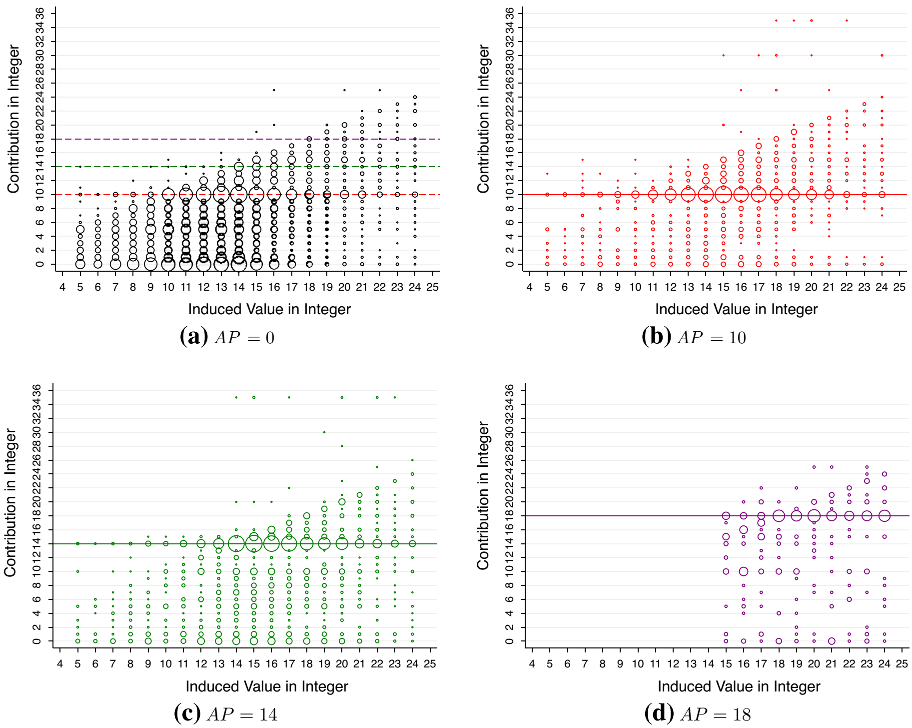


Fig. 4 Cumulative distribution of individual contribution by assurance payment. The figure shows the cumulative distribution from the pooled data of individual contributions on all six units



(a) $AP = 0$ **(b)** $AP = 10$

(c) $AP = 14$ **(d)** $AP = 18$

Fig. 5 The influence of assurance payments on individual contributions. This figure shows the frequency-weighted observed individual contributions at each induced value by *AP*. In each panel, the horizontal axis denotes the induced values, the vertical axis denotes the observed individual contributions. Both of induced values and contributions are rounded in integer for demonstration purpose. The size of the circles is proportional to the frequency of the contributions. The colored solid horizontal lines in panels (**b**) to (**d**) denote the corresponding assurance payment levels, and the colored dash lines in panel (**a**) indicate the three assurance payment levels for comparison

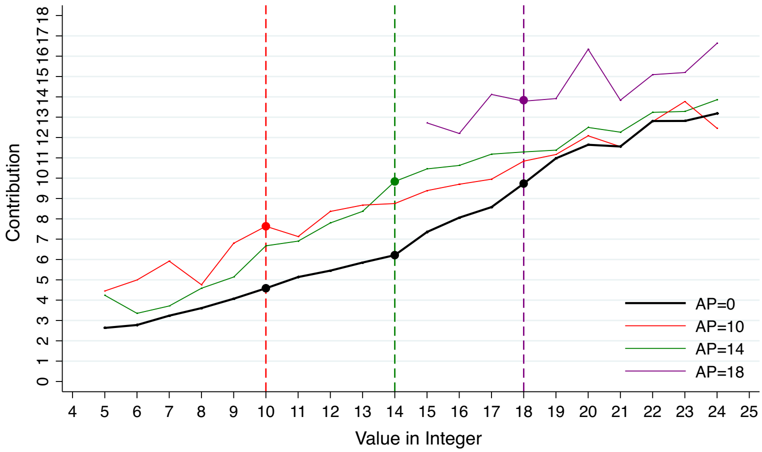


Fig. 6 Mean contributions by induced value. This figure demonstrates the relationship between average individual contributions and induced values in integer, where the assurance payment levels of 0, 10, 14 and 18 are denoted by connected black, red, green, and purple lines, respectively. The red, green, and purple vertical dash lines indicate the assurance payment levels of 10, 14 and 18, respectively. Since the assurance payment level of 18 is used only on unit 1, contributions under $AP = 18$ can be only observed in the value range of 15–25. Contributions under other assurance payment levels can be observed in the full value range of 5–25

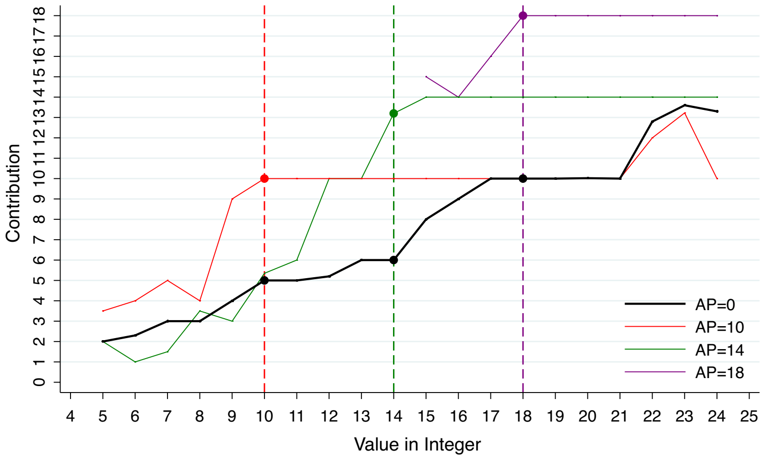
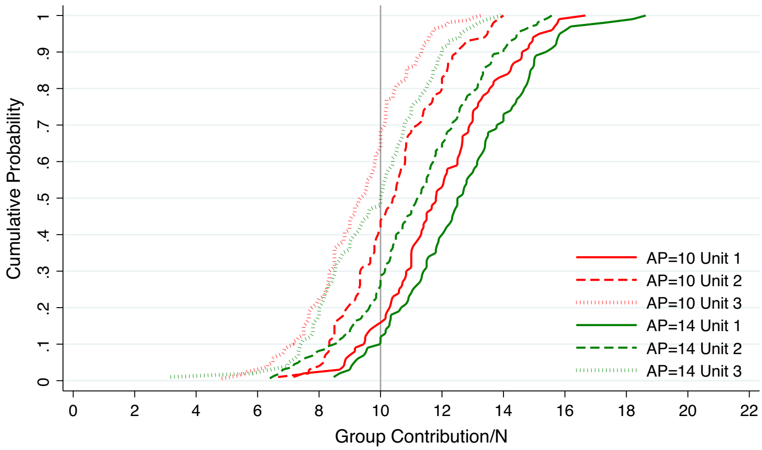
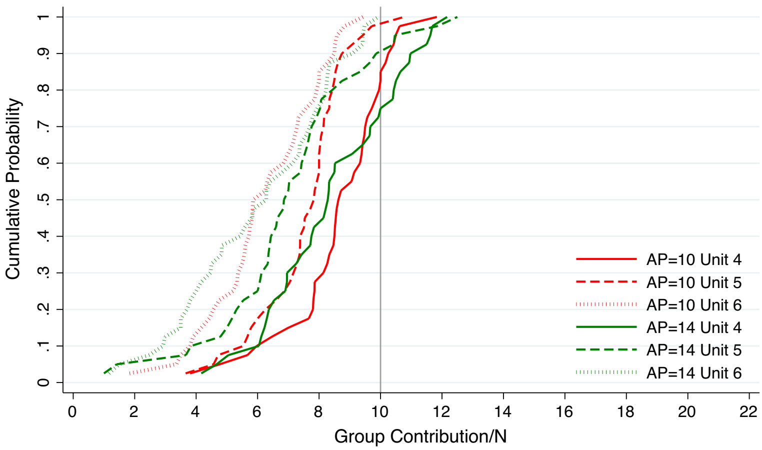


Fig. 7 Median contributions by induced value. This figure demonstrates the relationship between median individual contributions and induced values in integer, where the assurance payment levels of 0, 10, 14 and 18 are denoted by connected black, red, green, and purple lines, respectively. The red, green, and purple vertical dash lines indicate the assurance payment levels of 10, 14 and 18, respectively. Since the assurance payment level of 18 is used only on unit 1, contributions under $AP = 18$ can be only observed in the value range of 15–25. Contributions under other assurance payment levels can be observed in the full value range of 5–25

contributions at or above the equal-cost-share level, leading to significantly higher aggregate contributions.



(a) AP = 10 vs. AP = 14: Units 1 to 3



(b) AP = 10 vs. AP = 14: Units 4 to 6

Fig. 8 Cumulative distribution of normalized group contributions. This figure shows the cumulative distribution of group contributions normalized by the group size N under AP = 10 and 14 on each unit in two sets. Panel (**a**) is for units 1–3 and panel (**b**) for units 4–6, representing high and low value-cost ratios, respectively. The vertical grey line at 10 represents the group-size normalized unit cost

The effectiveness of assurance payments is determined by the level of the assurance payment and the value-cost ratio (the total group values divided by the cost) together. In our laboratory experiments with a maximum of six units, a sufficiently high assurance payment generally improves both of the provision rate and group contribution-value ratio more than a low assurance payment on the units (the first three) with relatively high value-cost ratios, but a low assurance generates a higher group contribution-value ratio with a smaller variance on the units (the last three) with low value-cost ratios, although a high assurance still induces higher provision rates on the last three units. In terms of a guideline for an optimal assurance payment scheme for multi-unit threshold public goods provision, a medium level of AP used on units with medium and high value-cost ratios is observed to induce the largest improvement on social surplus with both positive consumer and provider surpluses.[32]

Our results have important policy implications. First, the provision-point based mechanism with assurance payments could provide a powerful tool for non-market valuation, since the assurance payment could significantly reduce the free-riding incentive and induce a more accurate preference measure. However, this potential is not straightforward: while the assurance contract approach can lead to a higher revelation of gross social value by a group, the approach can incentivize individuals to strategize between the net benefit of provision and the net benefit of receiving an assurance payment. Second, this approach may help to facilitate a decentralized ecosystem service market, backed by a relatively high provision rate, which can be further optimized by flexible payment schemes. This implication may be especially important when providers (or market-makers) lack substantial information on valuation, although it comes at the risk of financial liability for assurance payments.

While this research focuses on evaluating mechanisms to leverage the demand for ecosystem services, the service providers may be identified through various reverse auction mechanisms where, for agroecosystem services, more cost-effective landowners or farmers are the likely winners. Our research assumes a constant opportunity cost, which can be relaxed in future research by assuming an increasing marginal cost to provide an additional unit if the reverse auction is successful in identifying the least costly providers. Also, the implementation of assurance payments in the field requires a third party who can make the assurance payments to eligible contributors in case of potential provision failures. The third party can be charities, researchers, or government agencies that have established credibility and sufficient funds to cover the assurance payments. However, our theoretical and experimental results imply that a properly chosen assurance payment may lead to a balanced budget and even a positive provider surplus on average over repetitions. Therefore, we think the assurance contract approach has the potential to mitigate the free riding or the coordination problems in threshold public goods provision and to support ecosystem services or other types of environmental benefits that have public goods properties with the help of a third party.

As in many public goods provision schemes, the devil will be in the details. Framing effects may matter to solicitation of contributions. In particular, would-be donors likely will find, that the assurance contract is unexpected relative to the common experience of solicitations for open-ended donations to a conservation organization, where such donations are not tied to a specific good (with money-back guarantee), and no one is offering to pay the would-be donor if a project fails to materialize. Individuals may initially question why any charity would offer to pay donors under such conditions. Framing the marketing communications may be critical. Research to evaluate alternative frames may prove critical to assisting the novice-citizen in grasping the concept, as has been seen in research involving novel incentive-compatible mechanisms (Kawagoe and Mori 2001). By this speculation, we again suggest that the assurance contract approach has practical potentials.

[32] Since the assurance payment involves a surplus transfer to consumers, it would be interesting to compare the performance of the assurance payment mechanism to a matching fund approach when the amounts of money to incentivize consumers are the same.

Appendices

Theoretical Framework and Proof

Proof for Proposition 4 When j units are provided, condition (a) ensures that the total bids on a provided unit just equal the cost, together with $\sum_i b_i^{j+1} < C$ we can conclude that only j units will be provided.

Individual i's profit from providing j units is

$$\pi_i^j = \sum_{l=1}^{j} v_i^l - j\left(C - \sum_{k \neq i} b_k^j \right) + I(b_i^{j+1} \geq AP^{j+1})AP^{j+1}, \tag{A.1}$$

where the term $\sum_{l=1}^{j} v_i^l - j(C - \sum_{k \neq i} b_k^j)$ represents the profit from the public goods without the assurance payment, $I(b_i^{j+1} \geq AP^{j+1})AP^{j+1}$ is the potential assurance payment from the $j+1$ unit since the assurance payment is only available on the first unit not provided, which depends on individual i's bid b_i^{j+1} and the assurance payment level AP^{j+1} with $I(\cdot)$ as the indicator function.

To eliminate the incentive to provide one more unit ($j+1$ units), we need to require no individual can obtain a higher profit by providing $j+1$ units. Individual i's profit from providing $j+1$ units is

$$\pi_i^{j+1} = \sum_{l=1}^{j+1} v_i^l - (j+1)\left(C - \sum_{k \neq i} b_k^{j+1} \right) + I(b_i^{j+2} \geq AP^{j+2})AP^{j+2}, \tag{A.2}$$

where the term $\sum_{l=1}^{j+1} v_i^l - (j+1)(C - \sum_{k \neq i} b_k^{j+1})$ represents the profit from the public goods without the assurance payment when $j+1$ units are provided. When providing j units are provided, we need $\pi_i^j \geq \pi_i^{j+1}, h > j$ so that no individual can be better by providing $j+1$ units unitarily, which implies,

$$\begin{aligned} v_i^{j+1} &+ (j+1)\sum_{k \neq i} b_k^{j+1} - j\sum_{k \neq i} b_k^j - I(b_i^{j+1} \geq AP^{j+1})AP^{j+1} \\ &+ I(b_i^{j+2} \geq AP^{j+2})AP^{j+2} \leq C, \forall i. \end{aligned} \tag{A.3}$$

To eliminate the incentive to provide $j-1$ units, we need to require no individual can obtain a higher profit by providing $j-1$ units. Individual i's profit from providing $j-1$ units is

$$\pi_i^{j-1} = \sum_{l=1}^{j-1} v_i^l - (j-1)\left(C - \sum_{k \neq i} b_k^{j-1} \right) + I(b_i^j \geq AP^j)AP^j, \tag{A.4}$$

where the term $\sum_{l=1}^{j-1} v_i^l - (j-1)(C - \sum_{k \neq i} b_k^{j-1})$ represents the profit from the public goods without the assurance payment when $j-1$ units are provided. We need $\pi_i^j \geq \pi_i^{j-1}$ so that no individual can be better by providing $j-1$ units unitarily, which implies,

$$v_i^j + j\sum_{k \neq i} b_k^j - (j-1)\sum_{k \neq i} b_k^{j-1} + I(b_i^{j+1} \geq AP^{j+1})AP^{j+1} - I(b_i^j \geq AP^j)AP^j \geq C, \forall i. \tag{A.5}$$

□

Proof for Corollary 1 When providing j units is the equilibrium outcome and assurance is not available, according to Proposition 3, we have

$$\begin{aligned}
&\sum_i \left(v_i^{j+1} + (j+1) \sum_{k \neq i} b_k^{j+1} - j \sum_{k \neq i} b_k^j \right) \leq \sum_i C \\
&\sum_i v_i^{j+1} + (N-1)(j+1) \sum_i b_i^{j+1} - (N-1)jC \leq NC \\
&\sum_i b_i^{j+1} \leq \frac{C(N + j(N-1)) - \sum_i b_i^{j+1}}{(N-1)(j+1)}
\end{aligned} \tag{A.6}$$

When assurance is available, according to Proposition 4, similarly we have

$$\sum_i b_i^{j+1} \leq \frac{C(N + j(N-1)) - \sum_i b_i^{j+1} + N_+^{j+1} AP^{j+1} - N_+^{j+2} AP^{j+2}}{(N-1)(j+1)} \tag{A.7}$$

where we define that $N_-^l = \left| \left\{ i : b_i^l < AP^l \right\} \right|$ and $N_+^l = \left| \left\{ i : b_i^l \geq AP^l \right\} \right|$. Note that when the assurance payment is constant or decreasing, and since the number of individuals qualify for assurance payment becomes lower at a higher unit as the induced value decreases, the presence of assurance payment will increase the upper bound of the total group contribution in equilibrium when $N_+^{j+1} AP^{j+1} - N_+^{j+2} AP^{j+2} > 0$. Also note that for $i \in N_-^{j+1}$, $C - \sum_{i \neq k} b_k^{j+1} \leq AP^{j+1}$ since otherwise individual i can just contribute AP^{j+1} on the $j+1$th unit to increase the profit by AP^{j+1}, therefore, we have

$$\begin{aligned}
&\sum_{i \in N_-^{j+1}} \left(C - \sum_{i \neq k} b_k^{j+1} \right) \leq \sum_{i \in N_-^{j+1}} AP^{j+1} \\
&N_-^{j+1} C - \sum_{i \in N_-^{j+1}} \sum_{i \neq k} b_k^{j+1} \leq \sum_{i \in N_-^{j+1}} AP^{j+1} \\
&N_-^{j+1} C - \left(N_-^{j+1} \sum_i b_i^{j+1} - \sum_{k \in N_-^{j+1}} b_k \right) \leq N_-^{j+1} AP^{j+1} \\
&N_-^{j+1} (C - AP^{j+1}) + \sum_{k \in N_-^{j+1}} b_k^{j+1} \geq N_-^{j+1} \sum_i b_i^{j+1} \\
&\sum_i b_i^{j+1} \geq C - AP^{j+1} + \frac{\sum_{k \in N_-^{j+1}} b_k^{j+1}}{N_-^{j+1}} \geq C - AP^{j+1}
\end{aligned} \tag{A.8}$$

□

Proof for Corollary 2 Here we impose a monotonic assumption so that individual i's bid is not decreasing when induced value increases. As a result, individual i's bid will be non-increasing when induced value is downward sloping as the unit number increases, or $b_i^j > b_i^{j+1}$. When equilibrium outcome is j units, we have $\sum_i b_i^{j+1} \leq C$. If $b_i^{j+1} < AP^{j+1}$, then $AP^{j+1} \geq C - \sum_i b_i^{j+1}$ since otherwise individual i can just contribute AP^{j+1} on the $j+1$th unit to increase the profit by AP^{j+1}. Also, since j is not provided, then individual i must receive a smaller profit providing $j+1$ units compared to when providing j units. Let $\tilde{b}_i^{j+1} < C - \sum_i b_i^{j+1}$ be the new bid needed to provide the $j+1$ units. Therefore,

$v_i^{j+1} - (j+1)\tilde{b}_i^{j+1} + jb_i^k < 0$, or $v_i^{j+1} < (j+1)\tilde{b}_i^{j+1} - jb_i^k$. According to the monotonic constraint, we have $v_i^{j+1} < (j+1)\tilde{b}_i^{j+1} - jb_i^k \leq \tilde{b}_i^{j+1} = C - \sum_i b_i^{j+1} \leq AP^{j+1}$.

When $j+1$th unit is not provided in the equilibrium and if $b_i^{j+1} < AP^{j+1}$, we find that $v_i^{j+1} < AP^{j+1}$, which implies that if $v_i^{j+1} \geq AP^{j+1}$, then $b_i^{j+1} \geq AP^{j+1}$. When $AP^{j+1} = \bar{v}^{j+1}$, and the number of individuals with values greater than or equal to $\bar{v}^{j+1}$ is great than C/v^{j+1}, the contributions from the set of individuals with values greater than or equal to $\bar{v}^{j+1}$ would be at least C, contradicting with the non-provision condition when the $j+1$th unit is not provided. □

Supplementary Tables and Figures

Table 6 The percentage of $B = C$ by AP and unit

AP	0	10	14	18
Unit 1	3.0%	0.0%	2.0%	0%
Unit 2	0.0%	3.0%	3.1%	NA
Unit 3	1.0%	5.6%	3.0%	NA
Unit 4	0.4%	2.5%	2.5%	NA
Unit 5	0.0%	0.0%	0.0%	NA
Unit 6	0.0%	0.0%	0.0%	NA

Lab Experiment Instructions

This is an experiment in the economics of decision-making. During the experiment, you will be asked to make a series of decisions. If you follow the instructions and make careful decisions, you can earn a considerable amount of money.

Experiment Overview

- You will be asked to decide how much money to offer towards the cost of several public goods in discrete units. This cost of the public good is predetermined and known to you.
- You will be randomly assigned to one of the two groups at the beginning. Your group members will change after each decision period.
- All members of your group receive a benefit that depends on the number of units being provided. The number of units provided depends on your decision AND those decisions of the other people in your group.
- Earnings in each decision period are based on how much you are willing to invest, how much you earn (your benefits) if the good is provided and the investment decisions of the others in your group. In some of the treatments, you may also earn extra money by satisfying our assurance contract requirement.

How You Earn Money

At the beginning of each period, you will be told the individual values (benefits) you receive if that unit of public good is provided. The individual value for one unit of public good can be different across people; someone may have a higher value than you, while the others may have a lower value than you. Your individual value will change after each decision period. You will then be asked to make contributions according to our rules. There are six public good units available in total and the cost is same for each unit.

You will be working with experimental dollars. Your initial fund will be 250 experimental dollars, which represents your fee for showing up today. Your earnings for each period will be added to or subtract from this amount. After the experiment, we will convert your earning to cash with a ratio 50:1; that is, if your balance at the end of the experiment is $1000, you will receive $20 in cash. There are three treatments in the experiment. You will be paid as you leave.

Group

Your group is important because the moderator, using a computer program, will evaluate the combined decisions (i.e. contributions) from each member of your group to determine the outcome. In this way, the decisions of every person in your group may impact your profit. You do not know others' contributions or benefits.

Communication

Communication is NOT allowed between participants once we begin today. If you have any questions during the treatments, please raise your hand.

Treatments, Periods

There are 15 decision periods in each treatment. We expect to finish the whole experiment within one hour and thirty minutes or so.

What you need to do?

Once the program is activated, please make a contribution for ***each*** public good unit. There are six units of public good available in total.

Your value

Your value on the first unit is randomly drawn from [15, 25], your value on the sixth (last) unit is randomly drawn from [5, 15]. Others' values are also randomly drawn from the same intervals; thus, someone may have a higher value than you, while some may have a lower value than you. Your value decreases from the first unit to the last unit.

How is your profit calculated?

- Your profit= Your benefit - Your cost.
- Your benefit= sum of your values for all the units that are provided.

Table 7 Two-factor random effects models of group contribution-value ratio for each unit after controlling for the group size

Group con-val. ratio	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
AP10	0.0354*	0.0316**	0.0701***	0.167***	0.180***	0.190***
	(0.0197)	(0.0169)	(0.0160)	(0.0214)	(0.0205)	(0.0242)
AP10*P10	−0.0207	0.00413	−0.00852			
	(0.0252)	(0.0216)	(0.0206)			
AP14	0.0619***	0.0658***	0.0931***	0.141***	0.124***	0.148***
	(0.0197)	(0.0169)	(0.0160)	(0.0214)	(0.0205)	(0.0242)
AP14*P14	−0.0298	0.0127	0.0209			
	(0.0251)	(0.0214)	(0.0205)			
AP18	0.137***					
	(0.0171)					
AP14*PDe		0.0214				
		(0.0214)				
AP10*PDe			−0.00828			
			(0.0204)			
P10				−0.0326*	−0.0625***	−0.0840***
				(0.0186)	(0.0178)	(0.0211)
P14				−0.0147	−0.0211	−0.0436**
				(0.0186)	(0.0178)	(0.0210)
PDe				−0.00121	−0.0119	−0.0195
				(0.0185)	(0.0178)	(0.0210)
Group size	0.0204	0.0155	−0.00765	−0.00935	−0.0186	−0.0246
	(0.0213)	(0.0169)	(0.0197)	(0.0357)	(0.0374)	(0.0376)
Constant (*Base*)	0.587***	0.550***	0.512***	0.452***	0.444***	0.444***
	(0.0178)	(0.0143)	(0.0151)	(0.026)	(0.0274)	(0.0283)
Log-likelihood	−228.5	−255.4	−268.3	−216.8	−224.2	−194.5
Number of observations	180	180	180	180	180	180
Number of periods	10	10	10	10	10	10

Standard errors in parentheses; ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$; AP10, AP14 and AP18 denote dummies for assurance payments of 10, 14 and 18, respectively; *P*10, *P*14, and *PDe* are the assurance scheme dummies

Your benefit depends on the number of units that your group collectively supports. You will receive your value for each unit supported. For example, if your group supported the first three units, and your values for the first three units are \$20, \$15, \$10, your benefit is \$20+\$15+\$10=\$45.

- Your cost = contribution on the last unit provided × number of units provided.

Your cost also depends on the number of units that your group could collectively support. Your cost is ***your contribution on the last unit provided*** times ***the number of units provided***. For example, if your group supported the first three units, your contribution on the third unit is \$5, then your cost \$5 × 3 = \$15.

- Under this situation, your profit = \$45−\$15 = \$30.

Table 8 Random effects tobit models of individual contribution by *AP*

Contribution	(1) PPM vs. $AP = 10$	(2) PPM vs. $AP = 14$	(3) PPM vs. $AP = 18$
Dummy of *AP*	3.315**	2.975***	13.94***
	(1.446)	(0.950)	(5.401)
$I(v \geq AP)$	−0.468	−1.365**	0.653
	(0.619)	(0.571)	(1.181)
$I(v \geq AP)$×Dummy of *AP*	1.123	4.031***	−8.653
	(1.470)	(1.121)	(5.863)
Value	0.406***	0.435***	0.429***
	(0.0683)	(0.0276)	(0.0177)
Value × Dummy of *AP*	−0.0449	−0.0407	−0.482
	(0.170)	(0.0738)	(0.322)
Value×$I(v \geq AP)$	0.0536	0.0858**	−0.00842
	(0.0707)	(0.0403)	(0.0592)
Value×$I(v \geq AP)$ × Dummy of *AP*	−0.0742	−0.189**	0.482
	(0.173)	(0.0840)	(0.342)
Constant (PPM)	0.0682	−0.168	−0.0531
	(0.589)	(0.362)	(0.292)
Log-likelihood	−23813	−24399	−17226
Chi-square	1322	1213	1070
Number of observations	2400	2400	2400
Number of periods (treatment-specific)	10	10	10
Standard errors in parentheses			

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

This table shows three random effects tobit regressions of individual contributions on treatment dummies to compare PPM and the assurance payment treatments with $AP = 10, 14, 18$, respectively. In all three models, the baseline is PPM, and we have the indicator variable $I(v \geq AP)$ to denote whether the value is greater than or equal to the assurance payment level *AP*, the dummy of *AP* to denote the treatment with the assurance payment level of *AP*, and the interaction term of $I(v \geq AP)$×Dummy of *AP*. Value denotes the variable of induced value

How to decide if a unit can be provided?

- We will compare the total contribution of your group for each unit with the public good cost for that unit, starting from the ***first unit***. If the group's total contribution on the first unit is higher or equal to the cost for the first unit, we continue to compare the contribution on the second unit with the cost of that unit, and so on.
- We will stop when the total group contribution for a unit is ***smaller*** than the unit cost.

All the numbers used in examples serve only illustrative purpose; please do not try to use these examples to guess what would actually happen in the experiment.

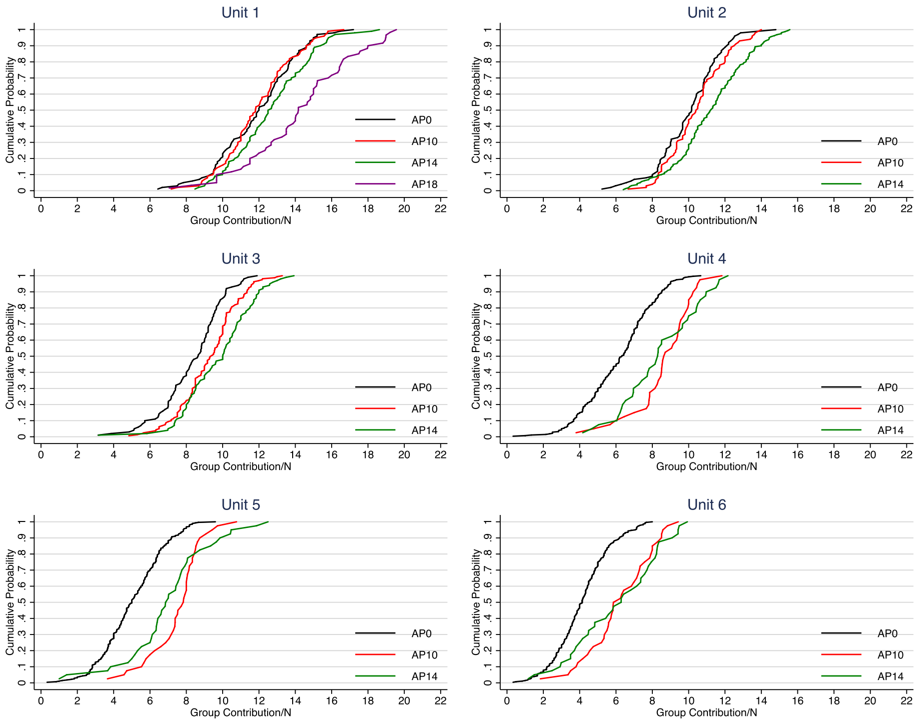


Fig. 9 Distribution of group contribution by assurance scheme. This figure shows the cumulative probability distribution of group contributions normalized by the group size N at each unit under different assurance payment levels

Assurance

In this treatment, we offer an assurance contract for the first three units. Your total profit is whatever you can get from providing the public good, plus any assurance payment whenever applicable. We try to protect you from getting zero benefits when you were willing to contribute above a certain level. That is, if your contribution on the first three units is higher or equals to a certain level, and if that unit is the first unit not provided, then we will compensate you an amount equal to the level we set with the table below, which we call the minimum contribution for assurance. Below is the minimum contribution for assurance you need to reach in order to get an assurance payment in case of provision failure; you may decide to contribute less if you wish, but then you will not be eligible to receive the assurance payment.

Unit	Minimum Contribution	Your Compensation
1	14 experimental dollars	14 experimental dollars
2	14 experimental dollars	14 experimental dollars
3	14 experimental dollars	14 experimental dollars

You receive assurance payment only for the first unit not provided. For example, if your values on the six units are $\{20, 15, 10, 5, 4, 3\}$, and contributions on the six units are $\{15, 14, 10, 5, 4, 2\}$, with the assurance,

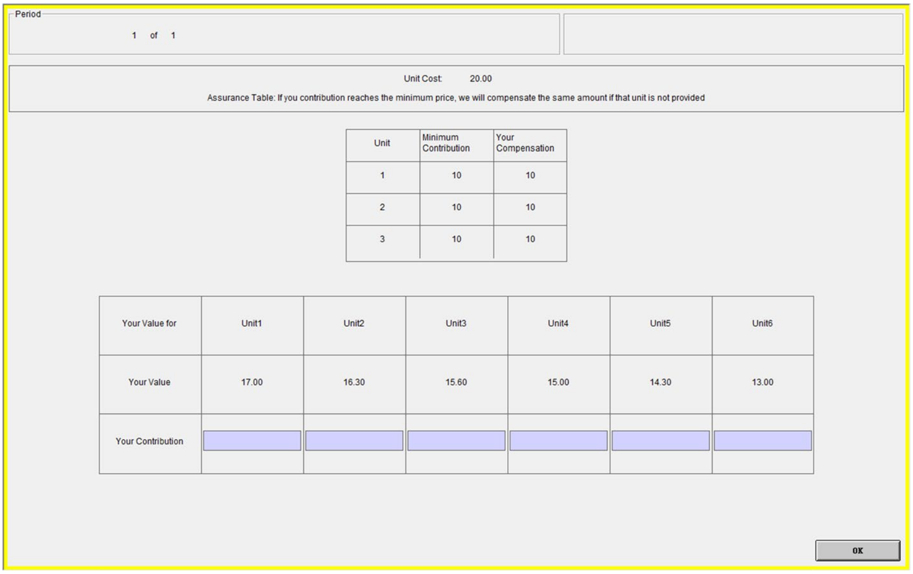
- If 0 units are provided, and we fail to provide Unit 1: Since your contribution on Unit 1 is $15, which is higher than $14, the minimum contribution, you will get a compensation from our assurance, $14. Thus, your total profit is $14. However, if you contributed lower than $14, say $10, your profit is $0.
- If 1 unit is provided, and we fail to provide Unit 2. Since your contribution on Unit 2 is $14, which equals $10, the minimum contribution, you will get a compensation from our assurance, $14. Thus, your total profit is your profit from providing 1 unit, $20-$15=$5, plus the compensation from our assurance, $14; therefore, your total profit is $5+$14=$19. However, if you contributed lower than $14 on the unit 2, say $8, your profit is $5.
- If 2 units are provided, and we fail to provide Unit 3. Since your contribution on Unit 3 is $10, which is smaller than $14, the minimum contribution, you will NOT get a compensation from our assurance. Thus, your total profit is your profit from providing 2 units, $20+$15-2*$14=$7. However, if you contributed more than (or equal to) $14 on Unit 3, say $15, then your profit is $7+$14=$21, since you get the assurance $14.
- We only provide assurance for the first three units.

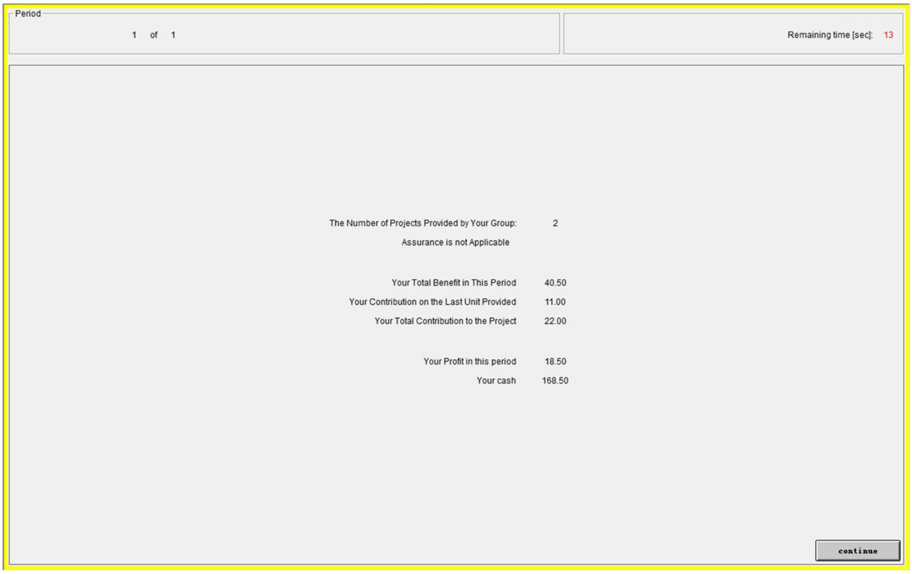
Quiz (4 mins)

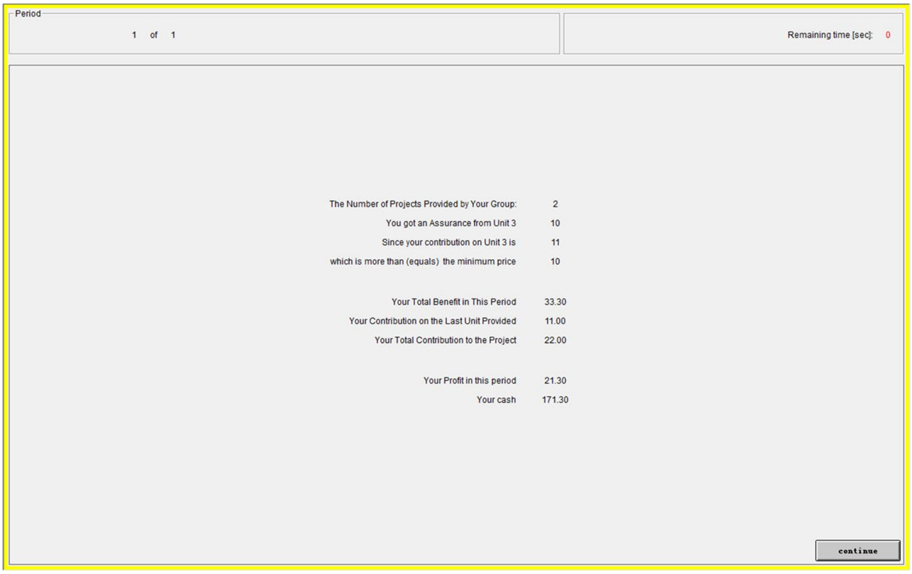
1. If your contributions on the first 4 units are $15, $10, $9, $6, respectively, and your group provides 2 units, what's your cost in this case?
2. If your contributions on the first 4 units are $15, $10, $9, $6, respectively, your benefits on the first 4 units are $20, $10, $5, $3, and if your group provides 2 units, what's your profit in this case? What's your profit if your group provided 1 unit? What's your profit if your group provided 0 units?
3. If there are five people in your group, their values are the same for the first five units which are {20, 18, 16, 14, 12}; their contributions on the first unit are {15, 15, 15, 15, 15}, their contributions on the second unit are {13, 13, 13, 13, 13}, their contributions on the third unit are {9, 9, 9, 9, 9}, their contributions on the fourth unit are {5, 5, 5, 5, 5}, and if the provision cost is 50. How many units are provided in total? What's the profit of one people? If only one unit is provided, what's the profit of one people?

At the end of the experiment, your earnings will be totaled across all periods and converted from experimental dollars to real dollars. You will be paid as you leave.

Now please make your decisions!


Period
1 of 1
Unit Cost: 20.00
Assurance Table: If you contribution reaches the minimum price, we will compensate the same amount if that unit is not provided
Unit
Minimum Contribution
Your Compensation
1 10 10
2 10 10
3 10 10
Your Value for
Unit1
Unit2
Unit3
Unit4
Unit5
Unit6
Your Value
17.00
16.30
15.60
15.00
14.30
13.00
Your Contribution
OK


Period
1 of 1
Remaining time [sec]: 13
The Number of Projects Provided by Your Group: 2
Assurance is not Applicable
Your Total Benefit in This Period 40.50
Your Contribution on the Last Unit Provided 11.00
Your Total Contribution to the Project 22.00
Your Profit in this period 18.50
Your cash 168.50
continue



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Declaration

Confict of interest The authors declare that they have no confict of interest.

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