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Cooperative agricultural production to exploit individual heterogeneity under a delivery target: The case of cotton in Uzbekistan

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ABSTRACT

This study argues that heterogeneous farms operating under a delivery target may yield significant economic benefits if they coordinate their production portfolio. To analyze the gains from cooperation, we simulate various cooperative game solutions over seven cotton producing farms in a bio-economic model of a water users association. The study results show that cooperation can fulfill multiple objectives: ensure the cotton production targets, increase farm profits and grain production, and reduce the pressure on water resources. We investigate a situation where farms differ in soil quality and distance to irrigation canals. The proposed modification in the national cotton procurement policy that utilizes the comparative advantages of cooperating cotton-producing farms can make the cooperative agreements economically attractive even among heterogeneous farms. It should be noted that the benefits offered from farm cooperation may be smaller or even vanish if transaction costs grow excessively in response to the heterogeneity of participating farms and the size of the cooperative. In addition, the economic benefits will not necessarily be distributed equally among participating farms and thus require the development of fair division rules. In this respect, net gain allocation schemes based on production costs, size and cotton output of farm cooperation are presented and discussed against the distinct social features of rural Uzbekistan.

1. Introduction

Due to poor rural infrastructure, costly contracting, indivisibilities in inputs, or monopolization, farmers often fail to reap the full benefits of market participation. To address these issues, they engage in formal and informal institutions of cooperation through which they realize economies of scale, improve their bargaining power, pool risks, or add value. While cooperatives are not a panacea to solve all problems of collective action in agriculture, there is a diverse set of successful models of agricultural cooperation, and many have been studied in detail both in the developed (cf Hansmann, 1996) and the developing world (cf Poulton et al., 2010). However, in the post-socialist transition economies, agricultural cooperation has often been misunderstood to be the same as collective agriculture under central planning. New models of farm cooperation emerged only slowly and where they did, cooperation has often been informal and sporadic (Lerman, 2004; Lerman and Sedik, 2014). Most observers will agree that, at least in the successor countries of the Soviet Union, there is no universally accepted model of farm cooperation that comes anywhere close to the agricultural service cooperatives known in the West. Evidence on viable role models is scant. In this study, we hypothesize that gains from cooperation may be realized in areas that have so far escaped the mainstream promotion of farmers' cooperatives. More specifically, we demonstrate how a cooperative agreement among farmers facing a delivery target permits an economically more efficient use of land and water. Such delivery targets are still widespread in the regulated commodity markets of Central Asian agriculture (Pomfret, 2008). As an example, we examine the case of Uzbekistan, where a group of farmers jointly manages the fulfillment of a cotton production target that currently each farmer in the group has to fulfill individually.

In Central Asia, cotton is among the most crucial crops. In Uzbekistan, which alone accounted for about 60% of cotton production in the former USSR (World Bank, 1992), its production has been linked to the interests of national export earnings and occupies up to a half of the country's total cropland area (FAO, 2013). Despite the declining trends of its domestic production and in favor of achieving grain self-sufficiency, Uzbekistan was among the top five cotton producing and exporting countries in 2010 (FAO, 2013). Despite the economic importance of cotton, its yields in Uzbekistan lagged behind those in neighboring countries, partly because the design of the state procurement policy, namely its order-control mechanism and low procurement prices, puts strong disincentives on its production (Djanibekov et al., 2013a).

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Given current and future projected changes in irrigation water availability, which for Central Asia is expected to decline (Siegfried et al., 2012), the main question is how to enable farmers in Uzbekistan to increase their economic benefits in view of persisting cotton production targets. The majority of previous studies considered adjustments in the design of the cotton policy, e.g., a shift from area-based to quantity-based targets, the complete abolishment of targets plus increasing the procurement prices, with the effects of higher farm revenues, higher cotton yields and lower pressure on irrigation water (Spoor, 1993; Pomfret, 2008; MacDonald, 2012; Djanibekov et al., 2013a). For instance, Djanibekov et al. (2013a) demonstrated that the abolishment of cotton production targets can ensure the same amount of cotton only at a substantial, but still realistic, increase of domestic prices of raw cotton, i.e., close to raw cotton prices in Kazakhstan.

With this work we contribute a different perspective on the modification of the cotton production targets in Uzbekistan. Compared to the previous studies, which focused on meso-level effects of restructuring the cotton procurement policy, we consider a situation where cotton-growing farms cooperate in fulfilling the cotton production targets such as to improve their individual economic results. In the cooperation agreements among cotton-growing farms we assume that the target is imposed on a group of farms, not at the level of a single producer. Participating farmers can negotiate who produces cotton and how much, so that the total harvest ensures the cotton production target of the group.

The objective of the study is to analyze how such cooperation can permit economically more efficient use of land and water by farms based on dissimilarity in their biophysical and geographic characteristics. By cooperating, the cotton-growing farms can complement each other in these and other characteristics and enhance the frontiers of their production decisions. We use the case of a water users association in the Khorezm province located in the Northwest of Uzbekistan in the lower reaches of the Amudarya River. The exploration of redesigning the procurement policy via incorporation of the farm cooperation aspects can be attractive to stakeholders as it does not introduce radical reforms but rather utilizes past and current features of farm organization and cotton production in Uzbekistan.

We analyze a hypothetical situation in which farmers have to fulfill the sum of their individual cotton production targets. This will ensure that the total cotton harvest is delivered and in turn allows us to avoid the analysis of potential sectoral and macroeconomic effects that may come in case of redesigning the cotton procurement policy. To model the farm cooperation we developed a cooperative farm game, which combined two drivers in forming cooperation: the net benefits and the transaction costs. We apply an approach proposed by Gerichhausen et al. (2009) to study how cooperation between heterogeneous farms can increase the cooperation outcomes through complementary effects in sharing the cotton production targets and in irrigation water use. Iliopoulos and Cook (1999) summarize various measures of membership heterogeneity such as members' geographic distance, their production commodities, and the differences in age, educational level, farm size, share of non-farm income and business objectives. Due to absence of farm specific socio-demographic information and for the model simplification the heterogeneity of farms in our case is measured by their land productivity and the distance to irrigation canals. To capture the cooperation between heterogeneous farms, we integrate a cooperative farm game into a bio-economic farm model. In addition, we define how the net benefits of cooperation can be distributed between the participating farms, given their measurable characteristics.

2. Agricultural cooperation under a delivery target: the case of Uzbekistan

2.1. An alternative model of agricultural cooperation

In the following, we consider a group of farmers that wish to maximize agricultural profits by pooling and sharing their individually received cotton production targets. The decision problem is subject to the group-internal distribution of land quality and access to irrigation water. Such a cooperative arrangement differs from both the Soviet model of forced collective production and the Western model of service and processing cooperatives (Table 1).

As in the Soviet collective farm model, in our case, an outside party, a government agency, is present that is interested in the fulfillment of the cotton target. However, it is indifferent whether farmers fulfill the production target individually or by pooling and sharing their individually received targets. Hence, the proposed model assumes a cooperative as a group of farmers who voluntarily choose to produce collectively and therefore form links with each other if they find that the group-based fulfillment of cotton production target is more beneficial. In this way, the participating farmers stay independent in terms of their asset ownership such as machinery and facilities. This model thus differs from the Soviet collective farm (*kolkhoz*) model which was based on forced asset pooling, joint production, and centrally planned delivery targets (Pryor, 1992). However, it is also distinct from the Western model of voluntary processing and service cooperatives. The Western model is typically driven by motives of improved bargaining power, adding value, or achieving economies of scale in machinery use (Deininger, 1995; Hansmann, 1996; Lerman and Sedik, 2014). Moreover, members in Western-style cooperatives do not face a delivery target problem.

In the proposed model, the economic gains would arise from the complementarity in biophysical and geographic characteristics which allows achieving the delivery target more efficiently. In other words, compared to the status quo of individual delivery targets without cooperation, the model suggests that there are gains from specialization by exploiting the heterogeneity of members. Cooperation is voluntary and limited to coordinating production portfolios in the light of cotton targets and agreeing on the division of benefits.

There is an interesting parallel to the problem of capacity utilization in conventional Western service cooperatives. Consider a service or processing cooperative that makes a large investment into a fixed asset providing services to the members, for example a processing plant or a large harvesting machine. Once the cost of this investment is sunk, a collective interest by the members emerges in utilizing this asset close to full capacity, in order to minimize average operating costs. This capacity target has the role of the delivery target in our model. Heterogeneity in member traits may make the capacity utilization of the fixed asset easier, for example if different farms use a machine at different times of the year (Aurbacher et al., 2011), produce different quality outputs (Hendrikse and Bijman, 2002), or realize their maximum milk output at different times (Nielsen, 1999). Complementarity effects similar to the one modeled below are then to be expected.

2.2. The background of cotton-grain farming in Uzbekistan

In terms of agricultural production, the farm restructuring process, and agricultural policies, Khorezm province can be regarded as representative for Uzbekistan, with some aspects such as irrigated agriculture and cotton cultivation also representative for Turkmenistan. Agricultural production in Khorezm occurs on about 270,000 ha of irrigated land and fully relies on irrigation water withdrawn from the Amudarya River. Cotton and wheat comprise almost 75% of the crop area (51% and 23% respectively). Other major crops are fodder crops such as maize with 9%, rice and vegetables both with 7%, and melons with 2% of the arable area.

Starting in 1992, farm individualization based on leasehold arrangements was promoted in which families received land through lease contracts for up to 50 years. Farm fragmentation increased between 1998 and 2006, when commercial farms replaced agricultural cooperatives and collective farms. Created in place of the large farms, commercial farms became responsible for almost the entire cotton production (Fig. 1a). These farms also contribute a significant share of water intensive rice production, the most profitable crop and the main cash earner

Table 1
Models of agricultural cooperation.

Model	Land pooling	Freedom to join/exit	Delivery target	Main driver of cooperation
Soviet collective farm	Yes	No	Yes	Political ideology
Western service and processing cooperatives	No	Yes	No, except to ensure capacity utilization	Increasing bargaining power, adding value, economies of scale
Model proposed here	No	Yes	Yes, collective	Internal gains from specialization based on individual heterogeneity
Current cotton production in Uzbekistan	No cooperation, individual delivery targets			

in Khorezm. Starting from 2009, farm fragmentation policy was reversed to farm reconsolidation mainly covering cotton-grain producing farms (Djanibekov et al., 2012). In 2011, there were about 4700 registered commercial farms in Khorezm occupying about 200,000 ha of agricultural land, while the remaining land is occupied mainly by rural households (OblStat, 2012). Cotton-grain growing farms consolidated into larger units of about 90 ha dominate the farm structure as they account for 42% of all commercial farms in Khorezm and occupy about 85% of total farmland (Fig. 1b).

2.3. The design of the cotton procurement policy

The design of the cotton procurement policy resembles the settings of the Soviet production targets such as the control over farmers' decision making and low procurement prices (Pomfret, 2008; Bobojonov et al., 2010; Kienzler et al., 2011; Djanibekov et al., 2013a). Djanibekov et al. (2013a) distinguish three central targets of cotton policy: location-, area- and quantity-based. According to the location-based target, farms have to grow cotton on fields considered the most suitable for cotton cultivation. The area-based target stipulates that the farms should allocate about half of their cropland for cotton cultivation. The quantity-based target implies that farms have to reach a certain level of cotton yield to fulfill the target assigned according to the quality of farmland and cotton cultivation area. The farms sell the entire cotton harvest to the state companies at prices below the potential border prices (MacDonald, 2012). As the state retains exclusive ownership of land, the failure to fulfill the cotton target can result in the termination of the land lease contract and the loss of land by a farm (Djanibekov et al., 2012). The cotton growing farms have to handle the cotton production targets individually with relative little bargaining power to negotiate the target levels of cotton cultivation area and harvest (Veldwisch and Spoor, 2008). Farms with poor land characteristics and located further away from canals have been experiencing losses from cotton production, while only few could make profits.

3. The simulation model

Our mathematical programming approach captures the features of cotton-growing farms in Uzbekistan and historically unobserved changes in agricultural policy of cotton production targets. This was realized in the Farm Level Economic Ecological Optimization Model (FLEOM), a bio-economic model developed in the GAMS environment at the scale of a water users association (WUA) in the ZEF/UNESCO research project (www.zef.de/khorezm.0.html), led by the Center for Development Research (ZEF) of the University of Bonn. At the core of FLEOM is a linear programming model that maximizes profits over seven modeled cotton-grain growing farms with a size range from 83 ha to 161 ha. The farms are located in the *Pakhlavan Makhmud* WUA on a total arable area of 822 ha (Fig. 2). Each farm is characterized by the soil quality of its fields and the distance to irrigation canals (discussed further as farm heterogeneity in Section 3.3). Four soil textures prevail: sand, loamy sand, sandy loam and loam. Silt loam layers together with sandy loams and loams constitute 80% of all soils (Sommer et al., 2010). The model database comprises agronomic and socio-economic characteristics of crops and farms, and was presented in detail in Sommer et al. (2010) and Djanibekov et al. (2013a).

3.1. The cooperative farm game

To understand the benefits from cooperation among biophysically and geographically different farms, we integrated a cooperative decision game into the FLEOM model. The cooperative farm game comprises S coalitions of N players. In our example of seven farms, there are 120 possible coalitions, i.e., 2^7 less 7 single-(non-cooperative) player coalitions and a zero coalition without any player. The value of each coalition $v(S)$ is the farm profits obtained by the FLEOM model for each

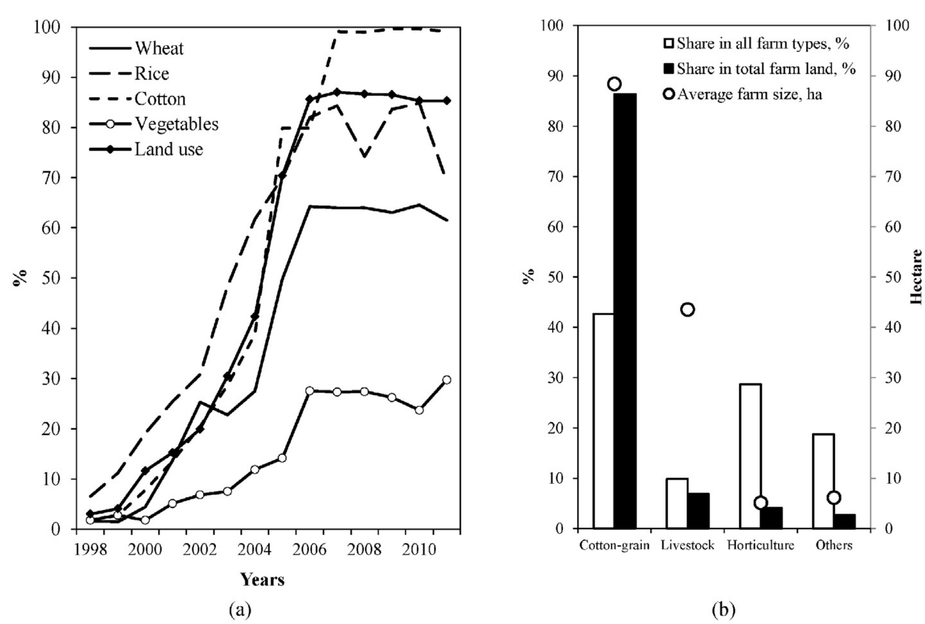

Fig. 1. Share of commercial farms in total land use and crop production in 1998–2011 (a), and types of commercial farms in the Khorezm province as of 2011 (b).

Fig. 2. Farm boundaries in WUA Pakhlavan Makhmud, Khorezm. Note: White areas include lands allocated to rural settlements, gardens/orchards, grazing and lakes.

cooperative game as presented in Eq. (6) in Appendix A. The cooperating farms thus face the problems of the selection of/agreement on the optimal cropping patterns and the allocation of the resulting net gains from cooperation.

A positive increment in the net benefits of coalition $\Delta(S)$ (Eq. (6) in Appendix A) indicates whether it is economically rational to form the coalition. However, while the $\Delta(S)$ shows the total economic effect of the coalition, the effect might differ for each farm. In other words, the positive sign of $\Delta(S)$ can be a result of large gains for some farms, while other farms may still lose from joining the coalition. While the positive increments in net benefits of coalitions imply that the economic gains of farms that benefit from cooperation can be shared with farms that lose from cooperation, a problem arises how to divide these benefits among the participating farms. A farm will accept unfavorable production plans only if its benefits are larger than those which it could achieve when fulfilling the cotton targets individually. Moreover, we assume that a farm will remain part of such cooperative only if its returns are proportional to its contribution.

We first analyze the potential of implementing the Kaldor–Hicks criterion of compensation (Eqs. (7) and (8) in Appendix A). This criterion approves a model solution if farms that are made better off can compensate those that are made worse off (Brent, 2008). When taking into account the transaction costs of cooperation, a Pareto optimal improvement in the system can be guaranteed in coalitions which lead to positive $\Delta(S)$. Compensations in net profits among participating farms can be used to make the Kaldor-Hicks criterion operational with the key idea to reduce the financial damage of disadvantaged farms as much as possible. This comes at the expense of those favored as well as guaranteeing that the disadvantaged participants will not be financially damaged when compared with the situation where they produce individually. Farm size, land quality, and the location in the irrigation system may also reflect varying bargaining power and connectedness of farms. Therefore, we explore how the net gains originating from the cooperation can be distributed according to measurable parameters of these farms, e.g., based on production costs, land size or the cotton production level.

3.2. Homogeneity in the objective function

In the model we assume that seven farms are homogenous in their objective function: they are all profit maximizers and similar in endowments of irrigation water per hectare of their cropland. In the remainder of this study, farms are referred to as A, B, C, D, E, F and G. Each farm can individually access a certain level of irrigation water, which we assume to be 14,000 m^3 ha^{-1}. This is the average annual irrigation water supply per cropland in Khorezm in 1998–2006, except for the 2000–2001 water scarce years (OblSelVodHoz, 2007).

The production activities comprise four major crops: cotton, maize, winter wheat and rice that occupied more than 76% of the sown area and required 82% of total irrigation water in Khorezm province in 1998–2006 (OblStat, 2012). For simplicity, inputs such as diesel, fertilizers, and labor were assumed constant with respect to the level of crop yield: each modeled farm applies similar crop-specific production techniques, yet crop yields vary with respect to the soil quality and the amounts of irrigation water applied (Table 2).

The settings of the cotton procurement policy are assumed to be identical for each farm in the model. According to the area-based setting, the cotton cultivation area in each farm should not be less than 50% of its total arable land. The quantity-based setting requires that farms produce cotton at an amount not less than 2.4 t ha^{-1} multiplied by the respective area set for cotton cultivation.

3.3. Heterogeneity in soil quality and water access

We assume a simple situation where the difference in soil quality and distance to irrigation canals affects farmers' decisions on land and

Table 2
Characteristics of crop production in WUA Pakhlavan Makhmud, Khorezm, in 2010.

Crops	Cropping calendar, month	Price, USD t^{-1}	Cost structure, USD ha^{-1}					Total costs, USD ha^{-1}	Crop water demand, m^3 ha^{-1}
			Seed	Labor	Diesel	Fertilizer	Other		
Cotton	I–XI	275	20	168	238	112	60	598	9251
Wheat	IX–VI	247	60	65	172	135	242	674	5596
Rice	VI–IX	753	121	174	399	101	830	1624	37,382
Maize	VI–X	275	96	53	113	101	185	548	3208

Table 3
Farm size, soil type and distance to irrigation canal in WUA Pakhlavan Makhmud, Khorezm.

	Farms						
	A	B	C	D	E	F	G
Farm size, ha	90	121	135	161	83	84	147
Land area according to soil type, ha							
Loamy	76	114	6	0	65	0	14
Loamy sand	6	1	13	5	2	9	32
Sandy	0	0	13	140	0	15	84
Sandy loamy	8	6	104	16	16	60	17
Average distance to irrigation canal, m	1655	517	1149	1213	435	561	1247

water use. In our study, Farms A, B and E have a biophysical advantage over the other farms as they are endowed with the largest share of land with loamy soils most suitable for cotton cultivation (Table 3). The soil types with low suitability for cotton cultivation are mainly found in Farms C and F. Yet, the distance to irrigation canals lowers the advantage in cotton production for Farms A and B. This is because irrigation of each individual field provokes a unique amount of conveyance losses in the channels depending on the field distance to irrigation canal (Sommer et al., 2010). Therefore, compared to Farm F, Farm C is further disadvantaged in cotton production due to the distance of its fields to the irrigation canal. Farms A, B and E find cotton cultivation profitable, while the other four farms lose money on this activity. The largest profits are observed for water intensive rice (Table 4).

The benefits from cooperation may occur when farms are not identical in their resource endowments (Gerichhausen et al., 2009). In our case this is demonstrated by the soil quality of farm land and the distance of the farm fields to the irrigation canal. Similar to the resource constraints are the policy regulations that identify, for instance, the upper or lower levels of certain production activities at the individual farm level. In this respect, the farms can pool their cotton production targets and utilize the complementarities in the quality of their fields. Furthermore, the benefits from farm cooperation may be greater when cooperating farms have more complementarities in resources. To depict the relation between the net benefits from cooperation and the difference of farms in resource endowments, we apply the method presented by Gerichhausen et al. (2009) and calculate a measure of farm coalition heterogeneity as presented in Eqs. (9)–(11) in Appendix A.

More homogenous coalitions display measures H^S closer to zero. For instance, among all two-player coalitions, coalitions between {B,E} and {C,F} have the lowest measure of heterogeneity, the highest value is observed for {B,G} (Table A in Appendix B). This indicates that Farms B and E, and C and F have very close soil-to-area ratios and distances to irrigation canals, while Farms B and G differ in these characteristics.

3.4. Scenario settings

To understand the prospects of farm cooperation in fulfilling the cotton production target compared with the situation where each farm faces a cotton production target individually, we simulate three situations with cooperative agreements (Table 5). In the BAUW scenario, farms face the cotton production targets individually, but cooperate in irrigation water use. The total amount of irrigation water available (Eq. (3a) in Appendix A) is now the sum of the water endowment of the individual farms that cooperate in water use (Eq. (3b) in Appendix A). The COTC scenario assumes a cooperative situation where participating farms are free to decide their own area of cotton cultivation but have to produce a predetermined amount of cotton for their coalition. In this case, the area-based setting of the production target (Eq. (4) in Appendix A) is relaxed, while the quantity-based setting (Eq. (5a) in Appendix A) is now the sum of individual production targets of farms participating in a coalition (Eq. (5b) in Appendix A). In COTC, we assume the farms still do not cooperate in water use. In the COTW scenario, in addition to pooling their cotton production targets, farms also cooperate in water use.

The scenario results are further compared with the business-as-usual (BAU) situation where farmers cooperate neither in water use nor in fulfilling the production targets. To reveal the benefits from a modified cotton procurement policy, we assume a scenario where the area-based setting of the cotton target is abolished, yet farms have to fulfill the quantity-based target individually (BAUC).

3.5. Transaction costs

Moral hazard, the free rider problem, and the risk of default from the cooperative agreement can impede cooperation. This is particularly true for coalitions of many and heterogeneous participants. To overcome the issues involving coordination, commitment and collective decision making, cooperation requires facilitation, negotiation and monitoring activities which cause costs. As the number of participants and the degree of heterogeneity increase, the transaction costs of cooperative will rise as well, possibly more than proportionally. The number of participants could be seen as increasing the likelihood of a bad actor hijacking the cooperative and hence the need for greater vigilance. The increased heterogeneity would increase the negotiating costs on rules operating the cooperative and distributing profits. Therefore, we first test the increment net benefits effect under two shapes of transaction cost functions, linear and quadratic, while later we focus only on the linear cost function. In the first formulation, the transaction costs are linearly positive in (a) the degree of farm heterogeneity, (b) the number of participating farms, and (c) the total area of cooperating farms as presented in Eq. (12a) (Appendix A). In the quadratic formulation, we assume that the transaction costs of coalitions are quadratic in the degree of farm heterogeneity and the number of participating farms, and linear in the total area of cooperating farms (Eq. (12b) in Appendix A).

We assume that farms hire additional personnel for monitoring, facilitating and advising their cooperative decisions. The number of these persons depends on the number of cooperating farms and the total land area utilized by a coalition. Each member of the coalition would spend some time on participating in meetings to discuss the

Table 4
Average potential crop yields and profits in different farms in WUA Pakhlavan Makhmud, Khorezm.

Farm	Cotton		Wheat		Rice		Maize	
	Yield, t ha^{-1}	Profit, USD ha^{-1}	Yield, t ha^{-1}	Profit, USD ha^{-1}	Yield, t ha^{-1}	Profit, USD ha^{-1}	Yield, t ha^{-1}	Profit, USD ha^{-1}
A	3.0	157	5.1	568	4.1	1440	3.7	472
B	3.1	222	5.1	598	4.3	1662	3.8	489
C	1.5	−141	4.9	529	4.1	1483	3.6	440
D	2.3	5	4.8	510	3.8	1130	3.4	378
E	3.1	242	5.1	588	4.3	1720	3.8	503
F	1.6	−94	4.9	545	4.1	1532	3.6	454
G	1.9	−65	4.9	532	3.5	981	3.2	325
Average in WUA	2.3	31	4.9	548	4.0	1374	3.5	425

Table 5
Scenario formulation.

Cotton production strategy	Water use strategy	
	Individual	Cooperative
Individual	BAU[a]; BAUC	BAUW
Cooperative	COTC	COTW

[a] No modification in cotton policy, the area-based setting of the cotton policy (Eq. (4) in Appendix A) is maintained.

irrigation and production plans, and the location and area of cotton fields such as to reduce the risks of deviating from cooperative agreements. We assume that a farmer values 1 h of his time with 21 USD, the average profit from one working hour among the seven modeled farms under the BAU situation (assuming that during one year a farmer works 313 days and allocates daily 10 h to his farm business).

For the cooperation in water use we assume 3 meetings annually, each lasting 2 h, at which farmers discuss and agree on their irrigation plans. The total of 6 h spent on irrigation coordinating meetings thus cost a farm manager 127 USD. In the cooperation of cotton production, each farm manager participates in 3 meetings annually, each lasting 4 h. Hence, annually, a manager spends 12 h for such meetings, valued with 254 USD.

We assume that participating farms would hire one person per 60 ha of arable land to monitor and report about the compliance to the cooperative agreements on cotton cultivation as well as to provide advice on cultivation techniques 8 months a year. Such a person would be paid 200 USD, or 27 USD ha^{-1}, monthly.

For cooperation in water use, we assume farms would hire people to monitor the irrigation plans during 8 months per annum. Such a person is also paid 200 USD monthly and responsible for an irrigated area of 200 ha, i.e., receives 8 USD ha^{-1}. Finally, each unit of the degree of heterogeneity of a coalition would require additional 12 person months to monitor and coordinate the efficient distribution of benefits among participating farms, and receive monthly 200 USD.

For the grand coalition in water use and fulfilling the cotton target in scenario COTW, the total transaction costs when calculated as a linear function are about 40,100 USD (Fig. 3), i.e. 49 USD ha^{-1}: seven participating farms each bearing the costs of participating in meetings on planning cotton cultivation and water use equal to 254 and 127 USD per farm respectively; expenditures for coordinating cropping and irrigation activities equal to the total cooperation area of 822 ha multiplied by 27 and 8 USD ha^{-1} respectively; and the grand coalition's heterogeneity index of 3.73 multiplied by 2400 USD. Respectively, for the grand coalition in COTW, the transaction costs as quadratic function are 80,500 USD, or 98 USD ha^{-1}. In a similar way the transaction costs of any other coalition can be calculated using the information of the size of farms from Table 3, and the number of participating farms and the measure of heterogeneity of each coalition from Table A in Appendix B.

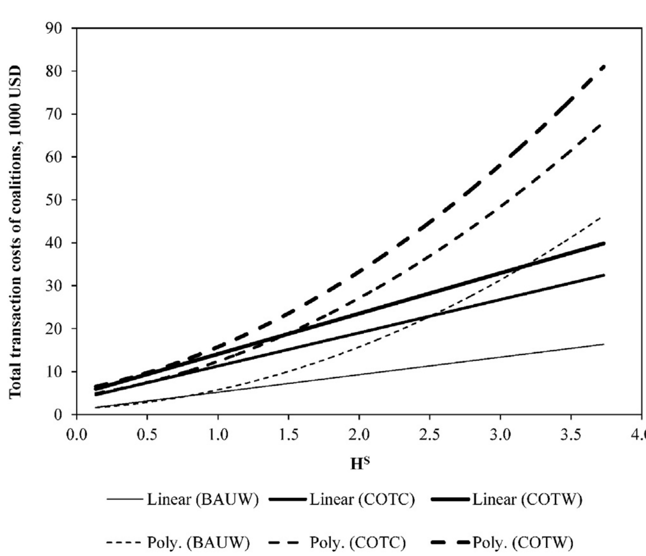

Fig. 3. Total transaction costs of different coalitions with respect to their heterogeneity H^S.

4. Simulation results

4.1. Increments in net benefits

The increment in net benefits $\Delta(S)$ of each coalition depends on the degree of heterogeneity of the participating farms H^S. When transactions costs are linear, coalitions of heterogeneous farms benefit most from cooperation. A farm cooperative endowed with better and poorer lands results in the most economically beneficial production plan. $\Delta(S)$ are larger for coalitions with a higher degree of heterogeneity (Fig. 4a), i.e., in our case the difference in the land productivity and the distance to the irrigation canal.

The benefits of a coalition are smaller than the sum of profits of individual farms in the BAU scenario, i.e., $\Delta(S)$ is negative, in particular in smaller coalitions. For the grand coalition N, the resulting $\Delta(S)$ is about 67,800 USD or 83 USD ha^{-1}. Accordingly, it can be economically

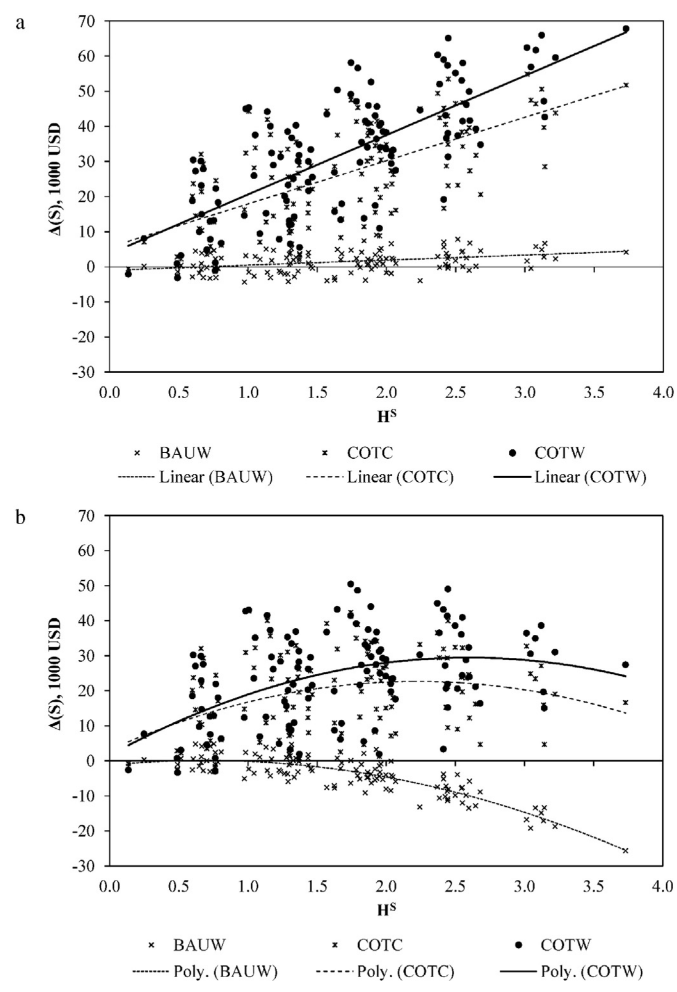

Fig. 4. Increments in net benefits $\Delta(S)$ and heterogeneity of coalitions H^S with linear (a) and quadratic (b) transaction cost functions.

beneficial to form larger and more heterogeneous coalitions, rather than establishing smaller and more homogeneous ones, particularly in cooperation both in cotton production and in water use (COTW).

Yet, a different picture is observed when transactions costs increase overproportionally with the number of participants and the degree of heterogeneity of the coalition (Fig. 4b). The comparison between Fig. 4a and 4b shows that the shape of the transaction cost function plays an important role in finding the optimal size and composition of coalitions (cooperatives). With a quadratic form of transaction costs, the smaller and relatively homogeneous coalitions face negative returns, while larger and heterogeneous cooperatives may offer a higher degree of complementarity and utilize comparative advantages of each participating farm. However, the economic benefits in large and heterogeneous cooperatives are also likely to vanish. Most interestingly, the increasing rate of transaction costs can make the pure cooperation in water use without modifications in the cotton policy economically unattractive (Fig. 4b). However, a coalition of farms cooperating in irrigation water use can achieve higher profits when farms also cooperate to fulfill the cotton targets. These results demonstrate that cooperation under the proposed version of the cotton procurement policy can serve farms a greater flexibility in decision-making and higher profits.

In the modeled system, pure cooperation in water use may result in the increase of grain production, as the shared irrigation water would be used more efficiently. As a result, the increase in heterogeneity in land productivity and in access to irrigation water leads to higher levels of grain production (Fig. 5a). Cooperation in fulfilling the cotton target can have higher gains, while the net gain in grain production is the largest when cooperation in water use is combined with cooperation in cotton production. This result reveals that in the modeled system of irrigated agriculture of Uzbekistan, cooperative decision making in the allocation of lands with different productivity can reverse the potential decline in wheat and maize production that may happen when farms receive individual freedom in cotton production. Bobojonov et al. (2010) and Djanibekov et al. (2013a) demonstrate that without such cooperation more flexible decision-making of farmers would increase the area of other crops, such as rice and fodder maize, at the expense of wheat cultivation.

The model results show that in each scenario the irrigation water would be used completely: the water availability constraints remain binding (Fig. 5b). In this case, given that the commodity and input prices remain unchanged, the shadow prices of water availability indicate the potential to reduce water pressure cooperatively. With increasing farm heterogeneity, the shadow price of water decreases (Fig. 5b), particularly when farms also cooperate in fulfilling the cotton production target (COTW). Furthermore, the range of the shadow price values of water narrows with increases in the heterogeneity of cooperating farms and in the size of their coalition. Hence, larger and more heterogeneous coalitions of farms in water use have more scope in easing water scarcity problems. This is in contrast to a more liberal policy scenario without cooperation: under more decision-making freedom and no cooperation, farms located closer to irrigation canals would decide to cultivate more water-intensive crops and thus reduce water availability further downstream (Djanibekov et al., 2013a).

The model results add to the discussion on the relationship between the characteristics of farms and the benefits of cooperation by demonstrating that complementary physical characteristics of farms, such as the productivity of farmland and the location in the irrigation network, can lead to higher payoffs from cooperation. When assuming that the government maintains the cotton procurement targets, the increase in prices of grain crops, particularly of rice, would increase the economic attractiveness of cooperation between farms that can complement each other's biophysical and geographical characteristics. The results demonstrate the importance of accounting for farm heterogeneity when considering farm cooperation as an alternative to farm consolidation (Djanibekov et al., 2012).

4.2. Division of net benefits from cooperative agreements

We examine the inter-farm transfers of costs and benefits at the level of the grand coalition as it comprises both favored and disadvantaged farms. A combination of both groups exemplifies a situation in which farms with land most suitable for cotton cultivation take over the production target of the entire coalition and thus allow other farms to focus on the production of commercial crops. As the form of

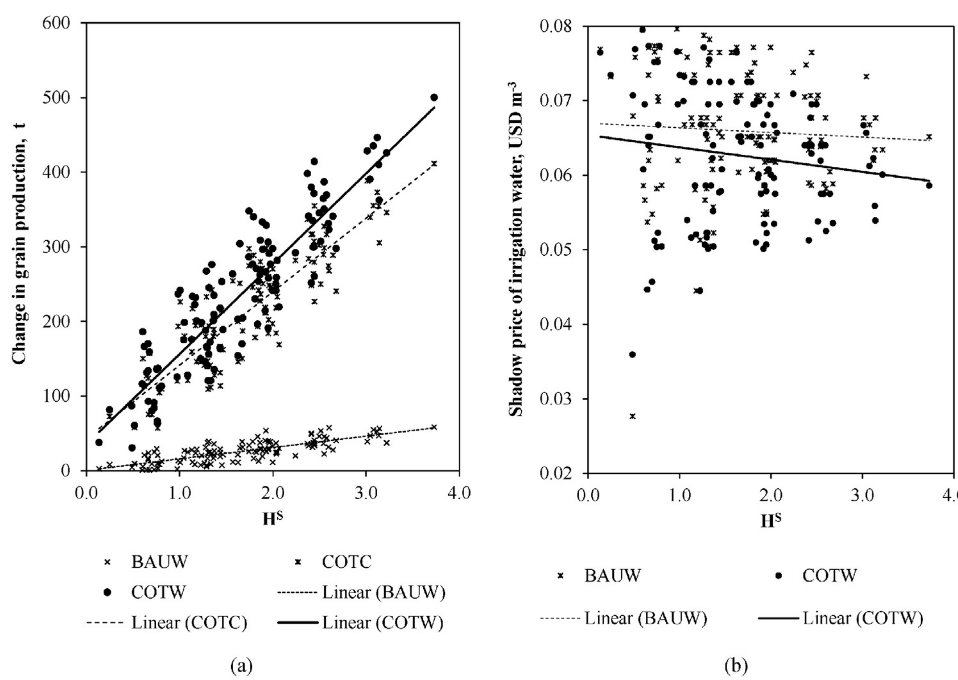

Fig. 5. Change in grain production (a) and shadow price of irrigation water (b) with respect to the heterogeneity of coalitions H^S.

Table 6
Individual farm profits with/without cooperative agreements with transaction costs.

	Farms							Total in WUA
	A	B	C	D	E	F	G	
BAU	50.1	90.8	74.0	67.1	64.8	53.1	63.5	463.4
No cooperation, modified cotton policy (BAUC), 1000 USD	54.2	91.3	84.2	70.1	69.0	56.7	72.6	498.1
% difference from BAU	8	1	14	4	7	7	14	7
Cooperation in water use (BAUW), 1000 USD	43.0	106.1	67.8	59.0	85.1	71.7	34.9	467.5
% difference from BAU	−14	17	−8	−12	31	35	−45	1
Cooperation in cotton production (COTC), 1000 USD	24.6	59.7	122.0	73.6	45.9	78.5	110.8	515.1
% difference from BAU	−51	−34	65	10	−29	48	74	11
Cooperation in cotton production and water use (COTW), 1000 USD	10.0	32.3	152.8	107.0	34.1	120.5	74.5	531.3
% difference from BAU	−80	−64	106	59	−47	127	17	15

the transaction cost function plays an important role in finding the optimal size and composition of coalitions, a specific analysis is required for each form. In the following, we focus only on the model results with linear transaction costs. It should be noted that the economic benefits in large and heterogeneous coalitions can be smaller or even vanish if a quadratic form of transaction costs of cooperation is imposed.

The sum of the profits of the individual production plans of all farms (A + B + C + D + E + F + G) in BAU is about 463,400 USD (Table 6). The modification of cotton policy via the abolishment of the area-based setting without cooperation (BAUC) brings an additional 7% gain for all farms, yet Farm B that operates at its maximum achievable cotton yields would gain only 1%.

The total profit of the grand coalition increases by only 1% if cooperation occurs solely in water use with positive transaction costs and an unmodified cotton policy (BAUW). This happens because the losses of farms with fields located further away from the irrigation canal (Farms A, C, D and G) almost offset the gains of farms located near the canal. It can be explained by conveyance losses in the irrigation canal, which in the water use cooperation favor the upstream farms at the expense of downstream farms.

Cooperation solely in fulfilling the cotton production target (COTC) increases the profits of the grand coalition by 3% when compared to individual management of a modified cotton procurement policy. However, farms which could benefit when facing the cotton production target individually, i.e., those with a large area of land suitable for cotton cultivation (Farms A, B and E), lose in all possible coalitions. The reason is that they agree with other farms to take up the largest share of the cotton target in favor of maximizing the net benefit of their coalition. In this way, the losses of the disadvantaged farms in cooperative agreements to fulfill the cotton targets offset the benefits of the advantaged farms (Farms C, D and F), although only partly.

In the cooperation occurring both in cotton production and water use (COTW), the biophysical attributes of farmland are decisive for the net benefits of cooperation. In this respect, Farm F located near the irrigation canal that is also endowed with a small share of area suitable for cotton cultivation, is the only farm that gains in each scenario, while Farm A located far from the irrigation canal and with the largest share of arable land suitable for cotton cultivation loses in each scenario.

These results demonstrate that while the increment in net benefit of a collective agreement is positive, some farms may lose from cooperation in favor of higher benefit of their coalition. In this respect, the development of fair rules to divide the net benefits from cooperation is likely to facilitate the development of more diverse and larger farm cooperatives. More diverse and larger cooperatives can be promoted by attracting farmers for whom the production targets would result in losses when managed individually. Farms would consider cooperating if the expected returns were higher than the ones achieved individually under the cotton target or its more flexible versions. Moreover, a farm would remain part of such cooperation if its return is in proportion to its contribution. Therefore, to facilitate the development of a more diverse and larger cooperation in water use and in cotton production, it is essential to develop a set of comprehensive rules according to which the increments in net benefits of farm cooperation are divided among participating farms. Such rules should guarantee that disadvantaged farms gain at least the amount which they could achieve when fulfilling the modified cotton target individually. In the following, we propose a financial compensation arrangement based on the Kaldor–Hicks criterion that leads to Pareto-optimal improvements taking into account solely the net gains (or losses) of each participating farm (Table 7).

According to this arrangement, Farms C, D, F and G shift a part of their increments in net benefits to Farms A, B and E to compensate their losses from cooperation when compared to the individual fulfillment of the cotton target. Through this cooperation scheme, Farms C, D, F and G would still gain an extra profit amounting to 33,100 USD in total.

However, such a division of net benefits may not be acceptable for some farms. If size as well as biophysical and geographic characteristics of the farm represents the power and connectedness of the farmer, these attributes should be considered when developing an acceptable scheme for distributing the extra benefits, thereby facilitating the participation of the disadvantaged yet ‘powerful’ players. In our case, Farms B and E are those with a high share of productive soils and close location to the irrigation canal. Accordingly, the extra profits of Farms C, D, F and G could be divided among the members in a way to guarantee fair division of benefits.

Table 7
Transfer of cooperative net benefits from favored to disadvantaged farms.

	Farms						
	A	B	C	D	E	F	G
Difference between increments in net benefits in grand coalition in COTW and BAUC, 1000 USD	−44.1	−59.0	68.6	36.9	−34.9	63.8	1.9
Share in net gains of grand coalition, %	0	0	40	22	0	37	1
Share in net losses of grand coalition, %	32	43	0	0	25	0	0
Division of net benefits from favored farms, 1000 USD	0.0	0.0	55.3	29.8	0.0	51.4	1.5
Compensation paid to disadvantaged farms, 1000 USD	44.1	59.0	0.0	0.0	34.9	0.0	0.0
Profits after compensation, 1000 USD	54.2	91.3	97.4	77.3	69.0	69.1	73.0
Increments in net benefits from cooperation, 1000 USD	0.0	0.0	13.3	7.1	0.0	12.3	0.4
Relative gain from cooperation, %	0	0	16	10	0	22	0.5

The basis for establishing the rules of distribution can be tangible (measurable) farm attributes such as the share of each farmer in the production costs of the coalition, the area of his arable land and his contribution to cotton output of the coalition. For instance, extra benefits can be distributed based on individual production costs (Table 8).

Farms C and D are the main contributors to the total production costs of the grand coalition. Yet, in this allocation solution the 'powerful' farms B and E have lower relative gains compared to other participants. Distribution based on farm size or on total cotton output of the coalition results in some farms having much higher relative gains from cooperation. Considering these three measurable farm attributes allows a more realistic distribution of the cooperation gains and is conducive to the economic success of the cooperation.

5. Social and cultural prerequisites for sustaining farm cooperation

The simulation exercise with seven cotton-grain growing farms shows that a modification in the cotton procurement policy can generate additional material incentives via cooperation of heterogeneous farms. Although larger and more diverse coalitions may not be the most economically beneficial, the cooperation can increase farmers' incentives to work for a common output by complementing each other. However, other attributes of the object of cooperation (e.g., cotton policy), environment (e.g., norms and networks) and participants (e.g., cotton-growing farms) can affect how the cooperation is organized (Ostrom, 2001). In addition to the material interest, the possible redesign of the cotton policy can provide an incentive for farmers to organize cooperation and to ensure its economic and institutional sustainability. The already existing land lease penalties for failing to deliver the production targets are shared by the participating farms. They may act as an enforcement mechanism and increase the farmers' commitment to work together.

Even so, a strong psychological resistance to cooperation among farmers and self-reliance on individual business was created by the long-lasting abuse of the concept of farm cooperation, e.g., via unfair treatment of its members, by the former Soviet regime (Lerman, 2004; Lerman and Sedik, 2014). Farm managers were often recruited from the professional staff of former collective farms. Their past experience of economic losses, poor yields, and lack of decision-making freedom tends to increase their hostility towards modern forms of cooperation. In addition, knowledge or good examples of how cooperation can be organized and, most importantly, knowledge about its economic benefits are scarce. A lack of farmers' flexibility in decision making due to the governmental control of land use to ensure the cotton production targets is another factor impeding the farmers' cooperative behavior. The experience of an erratic and unpredictable process of farm restructuring in the absence of land ownership has complicated any long-term planning of inter-farm partnerships (Djanibekov et al., 2012). The top-down manner in which the farm associations were introduced along the process of farm fragmentation impeded the foundation of institutional arrangements conducive to local collective action. An example is the water users associations established under the water resources management reforms, where farmers are supposed to act collectively to manage irrigation infrastructure and agree on water distribution (Abdullaev et al., 2010). Most water users associations continue suffering from underpayment and a lack of farmers' participation. Furthermore, in the absence of rules for conflict resolution, farmers avoid cooperation because they do not want to be overrun by larger co-participating farmers that are also economically and politically more powerful (Trevisani, 2007).

Despite these unfavorable conditions, informal forms of cooperation among farmers have emerged in Uzbekistan recently. They include mutual assistance on machinery use or sharing expert knowledge among narrow social groups such as friends, neighbors, or relatives (Veldwisch and Spoor, 2008; Shtaltovna, 2013). The farmers' response to the formal cooperation condition introduced by the modification in the cotton policy can be expected to be shaped by these existing informal institutions of daily social and economic interactions (Ostrom, 2000). Farmers face expressions of trust, norms and networks in their daily lives and they shape their selfish or reciprocal behavior towards cooperation (Djanibekov et al., 2013b). They are the prerequisites that may trigger and sustain cooperation when the government takes the necessary actions with respect to the cotton policy.

Table 8
Proposed schemes for distributing cooperative net benefits.

	Farms							Total in WUA
	A	B	C	D	E	F	G	
Distribution based on individual production costs in cooperation								
Production costs in COTW, 1000 USD	66.4	92.1	200.5	194.3	69.8	139.2	145.7	907.8
Share in total costs, %	7	10	22	21	8	15	16	100
Distribution of cooperative gains, 1000 USD	2.4	3.4	7.3	7.1	2.5	5.1	5.3	33.1
Net gains after compensation, 1000 USD	56.6	94.7	91.5	77.2	71.5	61.8	78.0	531.3
Relative gain from cooperation, %	4	4	9	10	4	9	7	
Distribution based on farm size								
Total farmland area, ha	90	121	135	161	83	84	147	822
Share in total WUA land, %	11	15	16	20	10	10	18	100
Distribution of cooperative gains, 1000 USD	3.6	4.9	5.5	6.5	3.3	3.4	5.9	33.1
Net gains after compensation, 1000 USD	57.8	96.2	89.6	76.6	72.3	60.1	78.6	531.3
Relative gain from cooperation, %	7	5	6	9	5	6	8	
Distribution based on total cotton production in cooperation								
Total cotton produced in COTW, t	151	187	73	194	147	50	156	958
Share in total cotton production, %	16	19	8	20	15	5	16	100
Distribution of cooperative gains, 1000 USD	5.2	6.4	2.5	6.7	5.1	1.7	5.4	33.1
Net gains after compensation, 1000 USD	59.4	97.8	86.7	76.8	74.1	58.5	78.1	531.3
Relative gain from cooperation, %	10	7	3	10	7	3	7	
Distribution based on combination of production costs, farm size and cotton output								
Sum over net gains in three cases, 1000 USD	11.3	14.7	15.3	20.3	11.0	10.2	16.7	99.3
Share in the total net gains, %	11	15	15	20	11	10	17	100
Distribution of cooperative gains, 1000 USD	3.8	4.9	5.1	6.8	3.7	3.4	5.6	33.1
Net gains after compensation, 1000 USD	57.9	96.2	89.3	76.9	72.6	60.1	78.2	531.3
Relative gain from cooperation, %	7	5	6	10	5	6	8	

First, it is worth mentioning that rural life in Uzbekistan is organized via networks of social ties establishing 'community' through a series of events at the settlement level where all members participate, or at the provincial level where local elites including farm managers are invited (Trevisani, 2007). This rural community platform can enhance communication between farmers allowing them to coordinate their activities in the cooperation. A simple form of cooperation as part of a social norms is the idea of *hashar* (Sievers, 2002), a form of conditional cooperation, where rural residents are willing to mutually support each other in response to the participation of others. Such a tradition of self-help in agricultural production, e.g., in maintaining irrigation canals and pumps, greatly contributes to solidarity and social order within a community and thus can contribute to the formation of voluntary cooperation (Troschke, 2011). For the considered heterogeneous cooperatives, 'powerful' farmers with higher levels of capital and other capabilities can take the lead in investing more in the facilitation of trust among participants, for example by organizing social events.

The existing internal networking formed by frequent interactions between farm managers, who previously held positions of managers, brigade leaders, and accountants in the former collective farm system, as well as outside linkages to the local administration still exist and determine the levels of farm output (Trevisani, 2007; Shtaltovna et al., 2012). Radnitz et al. (2009) showed that a high level of central control and regulation in Uzbekistan led to higher levels of trust within social groups than could be found in other Central Asian countries. They argue that central control discourages networking outside of a close-knit community, but may have a positive effect on the ability to maintain trust among those already in frequent interaction. Applying this finding to our study, the central regulation of the decision-making process in agricultural production via the cotton procurement policy may have a positive effect on the ability to maintain trust among farmers who already now interact frequently. In a transitional context, given such formal constraints in the current institutional environment, networking helps to overcome organizational problems of resource shortage and avoid transaction costs (Peng and Heath, 1996). Such professional ties between farm managers can act as internal self-regulating mechanisms which support the cooperation. For instance, as agricultural service provision became unreliable, particularly for field operations of cash crops, farmers extended their reliance on mutual self-help via the provision of machinery and agricultural advisory services to their counterparts (Shtaltovna et al., 2012). Networks can be relevant for sustaining cooperation since farmers from the same network have higher trust in each other. Every farmer possesses such networks to a different degree and utilizes them mainly during water and input shortages. Similar to complementing each other's biophysical and geographic features, members of a delivery cooperative could pool their outside networks for the economic sustainability of their cooperation and its legitimacy (Peng and Heath, 1996).

The Uzbek tradition of accepting authority such as parents and elderly and the concerns about social ostracism imply a high degree of obedience to formal and informal rules (Troschke, 2011). Together with a high degree of social consciousness observed in rural areas, such traditions can be used as an enforcement mechanism for farm cooperation. For example, the *mahalla* system is a formal institution of communal self-administration in Uzbekistan. It could be helpful to formalize the mediation of conflicts in cooperation and enforcement of commitments among farmers through social norms, customs and non-legal mechanisms of dispute resolution (Sievers, 2002; Van Assche and Djanibekov, 2012).

The proposed modification in the cotton policy would still imply the presence of top-down decision-making. However, the availability of options to choose whether to fulfill the cotton production target individually or on a group basis may encourage farmers, especially those that already interact frequently, to engage in cooperative agreements and benefit from the new opportunities of more flexible decision-making. Under such conditions, better knowledge of the possible gains from cooperation and the characteristics of other participants will help to build trust among farmers and make cooperation more likely (Cárdenas and Ostrom, 2004). The inter-farm and external networks may provide information about other farmers prior to cooperation, so that trustworthy members can be selected, or after cooperation for better monitoring and coordination. In the close-knit environment of rural Uzbekistan, networks can make the detection of defective behavior easy, whereas peer pressure can provide an effective punishment mechanism.

6. Conclusions

This study argues that heterogeneous farms operating under a delivery target may yield significant economic benefits if they coordinate their production portfolio. For the case of Uzbekistan, we looked at the benefits that would occur if the current area-based setting of the cotton production target was abolished, and farmers could individually decide on the cotton production area and location. The model results show that the analyzed version of the cotton procurement policy, as a state enforcement mechanism for sustaining cooperation, can ensure at least the same level of cotton output, while resulting in higher levels of food grain production and less pressure on irrigation water. These prospects of additional profit, grain output and reduced pressure on irrigation water provide a strong incentive for the bottom-up establishment of associations of cotton producers, analogous to water users associations.

According to the study results, the increments in net benefits from the cooperation would be larger when the participating farms differ in biophysical and geographic characteristics. This shows that the formation of cooperation in cotton production in Uzbekistan should take into account the biophysical and geographic heterogeneity of cotton-growing farms. While there is a net gain of cooperation at the group level, individual farms may be worse off than without cooperation. Specifically, farms endowed with larger areas of land most suitable for cotton cultivation may lose from participating in such cooperation. Hence, much attention has to be given to formalizing such cooperation. Particular attention should be paid to compensating those farms who contribute to the gains from cooperation by incurring higher production costs and a larger share of the cotton target.

As the costs of collective decision-making may grow excessively in response to the heterogeneity of cooperating farms and the size of the cooperative, the economic incentives to cooperate in fulfilling the cotton delivery target may vanish within large and heterogeneous coalitions. We, therefore, argue in favor of cooperation between cotton-wheat producing farms within the same local areas, such as the same irrigation canal. Although our analysis did not explicitly take into account factors which influence transaction costs such as trust and social norms, the fair division of cooperative gains, the amount of transaction costs foreseen for facilitating the cooperation as well as the requirement to fulfill the cotton production target can mitigate the possibility of morally hazardous behavior and help to build trust among participating farmers. In Uzbekistan, the local social institutions in which agricultural production and rural livelihoods are embedded can contribute to the sustainability of voluntary cooperation. However, the recent process of farm consolidation in the absence of land ownership as well as inequality in power relations between farmers, that can be associated to the inequality in farm size, land quality and location in the irrigation system, may impede the formation of cooperatives. In further studies on farm cooperation, it is necessary to understand the social and institutional environment shaping the farm interactions and their reciprocal or selfish behavior in a more rigorous way.

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Appendix A. *Formal structure of the simulation model*

The specification of the FLEOM model used in this study is presented in Djanibekov et al. (2013a). The core of FLEOM is a linear programming model. In the objective function (Eq. (1)), production activities (X) are optimized at an individual farm level by maximizing total farm gross margin (Z) of producing i crops on j soil types with c crop-specific gross margins (USD ha^{-1}). The model takes into account the available area (b) of j soil types in each farm (Eq. (2)) and the amount (w) of irrigation water supply (Eq. (3a) and (3b)). To depict the settings of the cotton policy, the model contains two policy constraints. Each farm has to allocate at least half of its arable land to cotton cultivation, i.e., the area ($\bar{x}$) set by the state with respect to the farm size (Eq. (4)). Furthermore, it has to deliver cotton output at an amount not less than the product of average achievable cotton yield ($\bar{y}$) and the target area set for its cultivation ($\bar{x}$) (Eq. (5a) and (5b)). Detailed description of model equations is given below.

The objective function of the model is the maximization of farm profits:

$$max\, Z_f = \sum_i \sum_j c_{ij} X_{fij} \tag{1}$$

where the index f stands for farms A to G, i stands for crops produced under different rates of water and fertilizer use on j soil types. c stands for the gross margin of each crop (in USD ha^{-1}), and X is the cultivated area of each modeled crop (in ha) on j soil types. The crop gross margins were calculated as output value per unit of activity less the sum of imputed costs such as seeds, fertilizers, pesticides, labor and machinery costs, land tax, and other fixed costs as observed in 2010.

Constraint of land endowments determines that each modeled farm allocates a specified area of arable land b with j soil type for cultivation of i crop on area X:

$$\sum_i X_{fij} \le b_{fj} \tag{2}$$

In addition, each farm receives a specified amount of water w that it uses for irrigation of i crops at irrigation rate k taking into account the conveyance losses:

$$\sum_i \sum_j k_{fi} X_{fij} \le w_f \tag{3a}$$

In cooperation in water use, farms pool their individual irrigation water limits:

$$\sum_f \sum_i \sum_j k_{fi} X_{fij} \le \sum_f w_f. \tag{3b}$$

To depict the cotton production target, the model contains two constraints. According to the area-based target, the area of cotton cultivation X should not be less than the one set by the state $\bar{x}$ (both in ha):

$$\sum_j X_{fij} \ge \bar{x}_{fi} \qquad \text{where } i = \text{cotton}. \tag{4}$$

In our case, each farm has to allocate at least half of its arable land to cotton cultivation.

According to the quantity-based target the average cotton yield y per hectare should not be less than the one set by the state $\bar{y}$ (both in t ha^{-1}). In our case, the amount of cotton produced by a farm should not be less than 2.4 t ha^{-1} multiplied by the area set for cotton cultivation $\bar{x}$:

$$\sum_j Y_{fij} X_{fij} \le \bar{y}_{fi} \bar{x}_{fi} \tag{5a}$$

By cooperating in cotton cultivation, the participating farms pool their individual production targets:

$$\sum_f \sum_j Y_{fij} X_{fij} \le \sum_f \bar{y}_{fi} \bar{x}_{fi} \tag{5b}$$

where i = cotton and Y is the yield of cotton and $\bar{y}$ is target yield set by the state (both in t ha^{-1}). In this case, the farm model determines an individual farm plan defined by the X land use activity for i modeled crops subject to land available b of j soil types, irrigation water availability w, and the policy constraints $\bar{x}$ and $\bar{y}$ such that the farm profit Z is at maximum.

For each possible coalition S between seven farms considered in the FLEOM, its increment in net benefits (profit), $\Delta(S)$, is defined as the difference between the total profit of the coalition, $v(S)$, and the sum of profits of individual farms, Z_f, participating in coalition S, which they would achieve when operating alone. $\Delta(S)$ allows the investigation of the relation between the gains from cooperation and the level of heterogeneity in resources of f farms in coalition:

$$\Delta(S) = v(S) - \sum_f Z_f \tag{6}$$

where f stands for Farms A–G.

The compensation scheme for the cooperative agreement is as follows:

$$CV_a = \Delta(S_a) \frac{\sum \Delta(S_d)}{\sum \Delta(S_a)} \tag{7}$$

$$CV_d = -\Delta(S_d) \tag{8}$$

where a and d stand for favored (advantaged) and disadvantaged farms. CV is the compensation value for favored and disadvantaged farms, respectively. $\Delta(S_a)$ and $\Delta(S_d)$ are the increments in net benefits of favored and disadvantaged farms, respectively, after introducing the cooperation.

The measure of heterogeneity for each coalition S is based on soil type and the distance to the irrigation canal of each individual farm f in the coalition. The ratios of individual soil structure to total arable land and the distance to the irrigation canal $\tilde{r}_i^f$ are normalized to make them independent of the units of measure as follows:

$$\tilde{r}_i^f = \frac{r_i^f - r_l}{r_h - r_l} \tag{9}$$

where superscript f stands for farm types, r_h and r_l respectively are the highest and lowest ratios of the area of different soil types to the total arable farmland as well as the distance to the irrigation canal observed for all modeled farms.

Using the normalized values $\tilde{r}_i^f$, the Euclidean distance value $D^{f,f1}$ is calculated for each possible coalition of farms to define the average difference between farms f and $f1$ ($f1$ is another farm) in coalition S.

$$D^{f,f1} = \sqrt{\sum_j \left(\tilde{r}_j^f - \tilde{r}_j^{f1}\right)^2} \tag{10}$$

If all farms in a coalition S have similar ratios of area of different soil types to their arable land and the distance to irrigation canal, i.e., $\tilde{r}_j^f = \tilde{r}_j^{f1}$, then these farms can be considered identical and their Euclidean distance value $D^{f,f1}$ is zero.

The measure of heterogeneity of each coalition S is defined as the sum of distances between farms participating in a coalition S, divided by the number of participants with $|S|$ greater than 1:

$$H^S = \frac{\sum D^{f,f1}}{|S|} \tag{11}$$

Similarly, if all farms are identical in their characteristics, the measure of heterogeneity of the coalition H^S would be equal to zero.

The transaction costs of each coalition ($c(S)$) are linearly positive in the degree of farm heterogeneity (H^S), the number of participating farms (M), and the total area of cooperating farms (A):

$$c(S) = \alpha H^S + \beta M + \gamma A \tag{12a}$$

The transaction costs of each coalition ($c(S)$) are quadratic in the degree of farm heterogeneity (H^S) and the number of participating farms (M), and linear in the total area of cooperating farms (A):

$$c(S) = \alpha \left(H^S\right)^2 + \beta M^2 + \gamma A \tag{12b}$$

where α is the salary of a full-time person hired to monitor and coordinate the efficient distribution of benefits among participating farms; β is monetary measurement of time spent by each participating farm manager to discuss the cooperative agreements; γ is the salary of persons hired to monitor and report about the compliance to the cooperative agreements on cotton cultivation and water use as well as to provide an advice on crop cultivation techniques.

Appendix B

Table A
Measures of heterogeneity of each coalition.

S	H^S	S	H^S	S	H^S	S	H^S	S	H^S	S	H^S
AB	0.49	ABC	1.29	BDG	1.37	ABEF	1.63	BDFG	2.04	ADEFG	2.60
AC	0.68	ABD	1.31	BEF	0.97	ABEG	1.68	BEFG	1.82	BCDEF	2.38
AD	0.70	ABE	0.76	BEG	1.13	ABFG	2.04	CDEF	1.78	BCDEG	2.55
AE	0.52	ABF	1.33	BFG	1.44	ACDE	1.97	CDEG	1.95	BCDFG	2.54
AF	0.78	ABG	1.30	CDE	1.37	ACDF	1.87	CDFG	1.65	BCEFG	2.37
AG	0.65	ACD	1.36	CDF	1.05	ACDG	1.89	CEFG	1.75	BDEFG	2.52
BC	0.77	ACE	1.24	CDG	1.17	ACEF	1.74	DEFG	1.93	CDEFG	2.41
BD	0.76	ACF	1.14	CEF	1.01	ACEG	1.93	ABCDE	2.44	ABCDEF	3.04
BE	0.14	ACG	1.29	CEG	1.35	ACFG	1.79	ABCDF	2.60	ABCDEG	3.14
BF	0.73	ADE	1.30	CFG	0.98	ADEF	2.00	ABCDG	2.65	ABCDFG	3.22
BG	0.81	ADF	1.43	DEF	1.33	ADEG	1.92	ABCEF	2.24	ABCEFG	3.02
CD	0.66	ADG	1.23	DEG	1.31	ADFG	1.95	ABCEG	2.43	ABDEFG	3.14
CE	0.66	AEF	1.27	DFG	1.18	AEFG	1.96	ABCFG	2.55	ACDEFG	3.12
CF	0.25	AEG	1.28	EFG	1.32	BCDE	1.86	ABDEF	2.45	BCDEFG	3.08
CG	0.61	AFG	1.37	ABCD	2.03	BCDF	1.92	ABDEG	2.41	N	3.73
DE	0.73	BCD	1.47	ABCE	1.63	BCDG	2.05	ABDFG	2.68		
DF	0.67	BCE	1.04	ABCF	1.85	BCEF	1.57	ABEFG	2.43		
DG	0.49	BCF	1.16	ABCG	2.00	BCEG	1.87	ACDEF	2.50		
EF	0.60	BCG	1.45	ABDE	1.67	BCFG	1.89	ACDEG	2.58		
EG	0.75	BDE	1.09	ABDF	2.07	BDEF	1.81	ACDFG	2.44		
FG	0.62	BDF	1.44	ABDG	1.95	BDEG	1.84	ACEFG	2.45		

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