Use of Tags and Group Selection to Engender Cooperation in n-player Snowdrift Game

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Abstract. Promoting cooperation in social dilemma games, particularly in multi-player settings, is a challenge with important implications for real-world systems. While many mechanisms exist to foster cooperation in iterated two-player games, the dynamics of cooperation in n-player social dilemmas are comparatively less understood. Techniques such as tagging, group selection, and pool rewarding have been applied to n-player games, but these approaches often rely on unrealistic assumptions and result in suboptimal cooperation levels. We present an evolutionary approach to engendering cooperation in the n-player Snowdrift game. Our hybrid method combines tagging with tournament selection to evolve individual strategies while utilizing group selection mechanisms for dynamic group restructuring. We evaluate the efficacy of this combined approach across varying cost-benefit ratios, population sizes, and group restructuring schemes. Experimental results show that our model consistently promotes and sustains high levels of cooperation in the n-player Snowdrift game. This work provides valuable insights into scalable cooperation mechanisms in multi-agent systems facing social dilemmas.

Keywords: n-person social dilemmas · Tags · Group selection · n-player Snowdrift.

1 Introduction

The emergence of cooperation in social dilemma situations has been widely studied across various disciplines, including biology, economics, psychology, and artificial intelligence, as real-world cooperation plays an important role in both human and artificial systems. Social dilemma scenarios that have received widespread attention include the *Prisoner's Dilemma* and the *Snowdrift* games [4] which are typically modeled as two-player games where each player can choose between one of two strategies: cooperate or defect. These studies try to identify the conditions under which cooperation will emerge as the predominant strategy.

Two-player games representing social dilemmas have been an active area of research. One-shot interactions in such social dilemmas incentivize defection as the dominant behavior, However, when these games are repeated among the same two agents or pairings of two agents from a larger population, cooperation can be sustained using various mechanisms such as direct, indirect, and network reciprocity, group selection, kinship, interaction neighborhoods, etc. [5, 12].

While two-player social dilemma games have been extensively studied, corresponding multi-player (n-player) games, despite their wide prevalence in real-world scenarios, have received less attention from the multiagent systems community. A key social dilemma in multi-player settings is the *public good game*, in which a group of n agents decides whether to contribute to a shared resource or public good [1]. Variants of public goods game include the n-player Snowdrift Game [15], which poses a social dilemmas in which cooperative agents are vulnerable to exploitation by defectors.

We evaluate a novel combination of the following complementary mechanisms to address social dilemmas in agent populations:

- Tags, or observable external features, have been used to both group players in a population and to decide how to interact with players [6, 7, 13].
- Tournament selection [11], comparing the utilities of randomly chosen agent pairs from the population, is used for individual-level selection pressure.
- Group selection is used to provide indirect, hierarchical selection pressure, to promote cooperative behavior in social dilemma situations [12, 14].

We simulate a population where each agent is assigned one of a finite number of tags. Agents assigned the same tag are part of a group that plays an n-person social dilemma game. Population evolution takes place via tournament selection, where two individuals, possibly from different groups, are compared based on their current fitness or utility level and a clone of the better fit individual is placed in its group while the worse fit individual is eliminated. This allows for dynamic group size modifications through individual selection. Larger groups may be split probabilistically or when they reach a size threshold. This group level selection adds a second level of selection pressure on the population. Agent strategies (cooperate/defect) are fixed and not adapted or evolved.

The integration of tags for grouping, tournament selection across the population for dynamic group sizing, and a combination of individual and group selection pressures provide evolutionary pressure that can promote cooperative strategy choices in n-person social dilemma games. By combining these mechanisms, it is possible to overcome the limitations of each approach when used in isolation, thereby promoting significantly higher rates of cooperation.

Through extensive experimentation, we will demonstrate the effectiveness of our proposed novel mechanism combination for fostering cooperation emergence and stability for multiplayer variants of the Prisoner's Dilemma and Snowdrift game. We conduct an ablation study and vary various parameters, including cost/benefit ratios, cooperation threshold required for payoff, group splitting method and criteria, initial number of tag groups, etc. Our results convincingly demonstrate the robustness of our proposed approach.

2 Related Work

Tags are observable features shared by groups of similar agents [7] that allow agents to signal their intentions and infer hidden properties about others. Research using tags to limit interaction to group members typically study two-person games [6, 10, 13] though some researchers have applied them to n-player games [3, 8]. *Hales et al* showed that agents could sustain cooperation with strangers by biasing interactions towards others who share a common tag or "cultural marker" [6]. *McDonald and Sen* explained why relatively long tags are needed to sustain cooperation in populations and identified higher tag mutation rate as another influential parameter determining the dominant strategy in evolving populations [10].

Group selection and dynamic grouping is another approach to fostering cooperation in n-person games. *Ji et al* studied the effects of grouping in an evolutionary n-person Snowdrift Game and found that the level of cooperation was significantly boosted when agents were grouped dynamically, as opposed to a static population of the same size [9]. *Traulsen and Nowak* proposed a minimalist stochastic model of multilevel group selection [14].

Chiong et al found that genetic algorithms and other evolutionary approaches allow agents to learn strategies that maximize fitness according to the outcomes of repeated interactions; however, their application to the Snowdrift Game, particularly its n-player variant, has been severely limited [2].

The combined effect of tagging and group selection has not been systematically studied in n-player games and under dynamic group restructuring. We hypothesize that their synergy helps cooperators cluster and gain competitive advantage against defectors, even at higher cost-benefit ratios, due to a multilevel selection dynamic that simultaneously rewards cooperative groups and successful individuals.

3 n-player Snowdrift Social Dilemma

In social dilemmas, individual incentives often conflict with group outcomes, leading to situations where self-interest might undermine collective welfare. One such game used to model these dynamics is the n-player Snowdrift game [4]. In the n-player Snowdrift Game, players must clear snow from a road so that they can proceed. If all players refuse to shovel the snow, i.e. they defect, then no one benefits, leading to a worse outcome for all. If all players shovel the snow, i.e. they cooperate, then they share the benefits, leading to a higher collective payoff. If some players cooperate while others defect, the cooperators still benefit but less so than if everyone had cooperated. Defectors benefit from the cooperation of others without contributing themselves. We use a standard formalization of the payoff structure for the n-player Snowdrift Game [15] and introduce two modified variants by incorporating a cooperation threshold. The payoff structure for the standard version of the n-player Snowdrift Game follows:

> *Payoff for defectors is b if $N_C > 0$ and 0 otherwise. Payoff for cooperators is $b - \frac{c}{N_C}$ if $N_C > 0$ and 0 otherwise, where b is the benefit, c is the cost, and N_C is the number of cooperators.*

For the first variant of the n-player Snowdrift Game, including a fractional cooperation threshold, the payoff structure follows:

Payoff for defectors is b if $\frac{N_C}{N} \geq fct$ *and 0 otherwise. Payoff for cooperators is* $b - \frac{c}{N_C}$ *if* $\frac{N_C}{N} \geq fct$ *and 0 otherwise, where fct is the fractional cooperation threshold and N is the number of agents.*

For the second variant of the n-player Snowdrift Game, including a constant cooperation threshold, the payoff structure follows:

Payoff for defectors is b if $N_C \geq ct$ *and 0 otherwise. Payoff for cooperators is* $b - \frac{c}{N_C}$ *if* $N_C \geq ct$ *and 0 otherwise, where ct is the constant constant cooperation threshold.*

4 Methodology

Our simulation for tags and group selection in a social dilemma is detailed in Algorithm 1. A simulation first initializes the population with N_{Agents} agents and N_{Groups} groups. Simulations are run for $N_{Generations}$ generations, and each generation is broken into three stages:

Social Dilemma Stage (lines 5 to 9): Each group participates in an n-player social dilemma, where every agent in the group receives a reward.

Tournament Selection Stage (lines 10 to 16): Each agent competes in a tournament against a randomly selected agent from the population. The agent with the lower reward adopts the tag and strategy of the agent with the higher reward and migrates to that agent's tag group.

Group Selection Stage (lines 17 to 21): Each group is tested for selection using a group selection criterion. Let $|G|$ be the size of group G, i.e., the number of agents using the corresponding tag. The decision to split a group is based on the group size.

Two *group selection criteria* were implemented. The first criterion selects a group G if the group's size is greater than the group selection threshold, i.e., $|G| \geq gt$. The second criterion selects a group with a probability equal to the group's size divided by the group selection threshold, i,e., probability of selection group G is $\min(1, \frac{|G|}{gt})$. The selected group G is split into two groups.

One of the split groups keep the current group tag, while the other, G' migrates according to one of two *group splitting methods*. The first method is described in Algorithm 2, where an existing empty group is randomly chosen, and if no such group exists, a new empty group is created. Let G_d be this destination group which is given a tag from other tags of agents in other groups. The members of G' are relocated to the empty group G_d with no modifications to their strategy but they adopt the new tag assigned to G_d. The second method is described in Algorithm 3, where the smallest group G_s is chosen as the destination group. If $G = G_s$, the procedure terminates with no change in the groups or any migration. Otherwise, a set of agents $G' \subset G$ are migrated from G to G_s such that afterwards the two groups are approximately the same size (their sizes can differ by a maximum of one agent). Agents in G' retain their strategies but adopt the tag of G_s while each existing member of G_s randomly adopt the strategy of an agent from G'.

Algorithm 1 Use of tags and group selection in social dilemmas

procedure SIMULATION(N_{Agents}, N_{Groups}, $N_{Generations}$, r, ct or fct, gt)
    population ← createAgents(N_{Agents})
    groups ← assignGroups(population, N_{Groups})
    for generation = 1 to $N_{Generations}$ **do**
        for all group in groups **do**
            actions ← getActions(group)
            rewards ← socialDilemma(actions, r, ct or fct)
            assignRewards(actions, rewards)
        end for
        for all agent in population **do**
            other ← randomAgent(population)
            if agent.reward < other.reward **then**
                cloneAgent(other)
                deleteAgent(agent)
            end if
        end for
        for all group in groups **do**
            if shouldSplitGroup(group, gt) **then**
                SPLITGROUP(groups, group)
            end if
        end for
    end for
end procedure

Algorithm 2 Split group into an empty group

procedure SPLITGROUPTOEMPTY(groups, group)
    dest ← an empty group from groups or a new group if none are empty
    migrants ← half of the members of group
    group.remove(migrants)
    dest.add(migrants)
end procedure

5 Results

In this section, we present an overview of the typical simulation of the n-person Snowdrift game as well as the results from an ablation study and varying various parameters in our model. Unless otherwise stated, results are averaged over 100 simulations, each running for 150 generations. Simulations were initialized with 20 groups and 100 agents, using both group selection criterion 1 and group selection method 1.

5.1 Effect of Group Selection

Figure 1 shows the effect of group selection on cooperation. Without the use of group selection, cooperation can sometimes dominate in the population; however, this only occurs roughly 7% of the time.

Algorithm 3 Evenly split groups into the smallest group

procedure SplitGroupEvenlyToSmallest(groups, group)
  dest ← chose the smallest group from groups
  if group ≠ dest **then**
    migrants ← enough agents from group s.t. the number of agents in both groups are approximately equal.
    for all agent in dest **do**
      agent.strategy ← the strategy of an agent randomly selected from group
    end for
    group.remove(migrants)
    dest.add(migrants)
  end if
end procedure

When group selection was introduced, after 100 generations, only cooperating or defecting groups remained in 89% and 0.4% of simulations, respectively. In the remaining 10.6% cases, the population never fully converged, but more of these runs resulted in a majority of defectors. Further analysis of individual simulations suggests that group selection typically isolates groups of cooperators in the population. Once every group contains only cooperators or only defectors, cooperative group payoff dominates while group of defectors receive no payoff. Hence cooperative groups increase in size and ultimately splits and takes over smaller groups of defectors. This process is evident from generation 24 onwards in Figure 2.

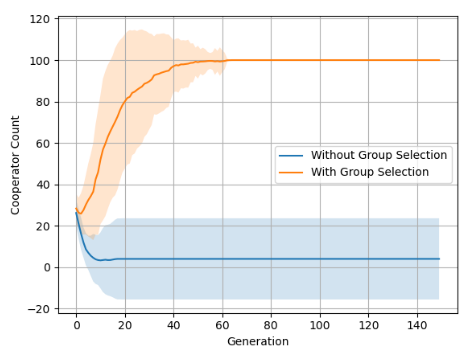


Fig. 1: Cooperation Over 150 Generations With and Without Group Selection.

5.2 Group Cooperation Per Generation

Figure 2 illustrates a typical simulation for a Snowdrift game with parameters $r = 0.3, gt = 10, ct = 1$, employing group selection criterion 1 and group selection method 1. The figure displays the size and ratio of cooperators to defectors in each group over 50 generations. The size of a group is represented by the size of its marker, while the ratio of cooperators to defectors is indicated by the marker color, with green representing cooperation and red representing defection. It should be noted that groups are sorted from largest to smallest. These results are analyzed in Section 6.

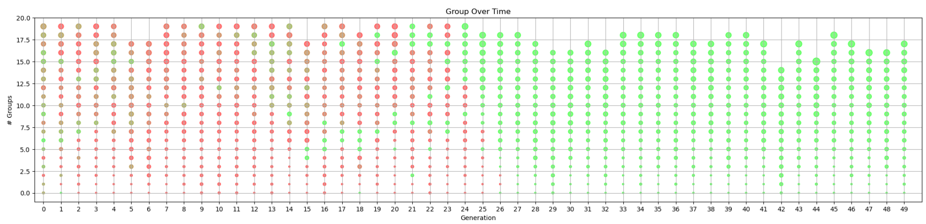


Fig. 2: Cooperation Level in Each Group Per Generation.

5.3 Varying Cost-Benefit Ratio

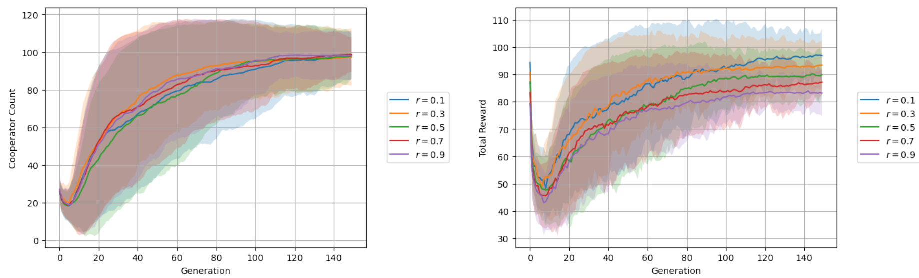
Figure 3 depicts the number of cooperators and total reward received across generations. Varying r does not significantly affect the final number of cooperators in the population. Additionally, the rewards in the SD game are scaled while keeping benefit costant at 1. Hence, higher total rewards are obtained with smaller values of r.

5.4 Varying the Group Split Threshold

Figure 4a shows the number of cooperators in each generation with group selection criterion 1. Figure 4b shows the cooperation rate for each generation with group selection criterion 2. Furthermore, the use of group selection criterion 2 results in more cooperators than criterion 1 in most cases. Further analysis of these results is presented in Section 6.

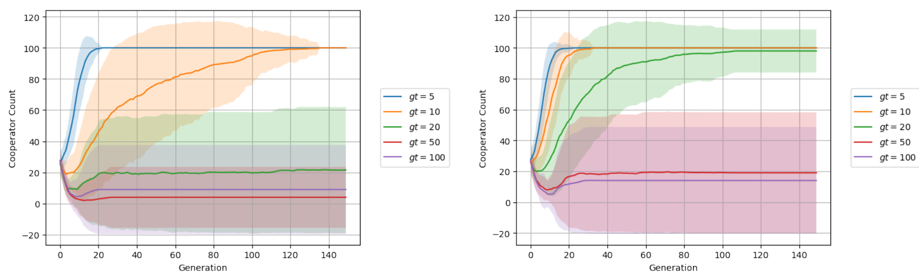
5.5 Varying the Cooperation Threshold

We also examined the effect of varying the cooperation threshold on the number of cooperators and the total reward. Figures 5 and 6 display the cooperation rate and total reward over 150 generations given a constant cooperation threshold and a fractional cooperation threshold, respectively. In Figure 5a, we observe that with $ct = 0$, defection prevails because cooperation is not required to receive a benefit. Furthermore, when $ct = 10$, neither cooperation nor defection emerges, as no group has enough cooperators to receive rewards. Additionally, Figure 5a indicates that when $ct = 3$, cooperation is achieved more quickly than with



(a) Cooperation level per generation (b) Total reward per generation

Fig. 3: Effect of r on cooperation level & reward over generations; $ct = 1$, $gt = 10$.



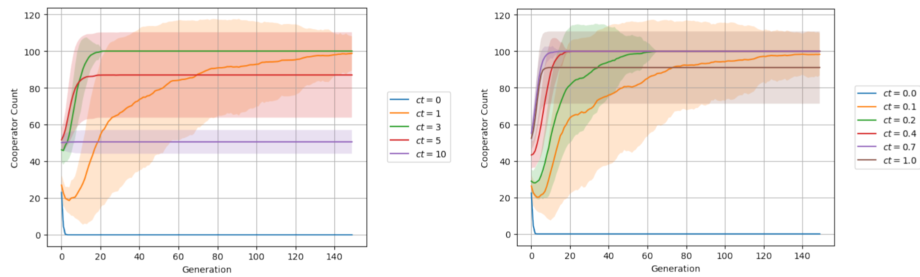
(a) Group Selection Criterion 1. (b) Group Selection Criterion 2.

Fig. 4: Effect of gt on cooperation level over generations; $r = 0.3$, $ct = 1$.

$ct = 1$; however, the total reward at the end of the simulation when $ct = 1$ surpassed that achieved with $ct = 3$. Similar patterns are evident in Figure 5b, where lower fct values lead to a delayed convergence to cooperation. These findings are discussed further in Section 6.

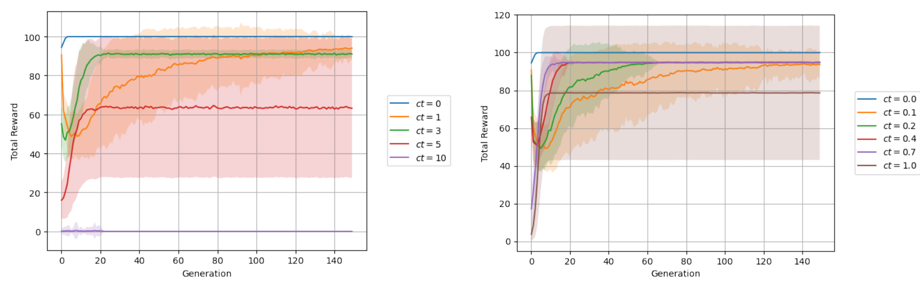
5.6 Varying Group Count and Selection Methods

We then examined the effects of varying the initial number of groups and the group selection method. Figures 7a and 7b present the number of cooperators in the population across generations, varying the number of initial groups. In Figure 7a, which employs the first group selection method described in Algorithm 2, we observe that a greater initial number of groups fosters cooperation more effectively. Notably, cooperation does not fail to emerge even when $N_{Groups} = 1$. Figure 7b employs the second group selection method described in Algorithm 3, which does not introduce new groups into the simulation as the first method does. We observe that defection is more likely to dominate when the second selection method is used. Additionally, when the population neither converges to defection nor cooperation, the number of cooperators is lower with the second



(a) Constant Cooperation Threshold. (b) Fractional Cooperation Threshold.

Fig. 5: Effect of ct & fct on cooperation level over generations; $r = 0.3$, $gt = 10$.



(a) Constant Cooperation Threshold. (b) Fractional Cooperation Threshold.

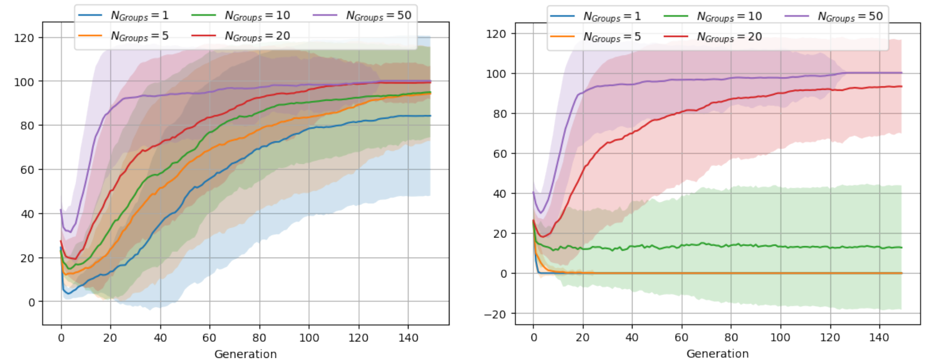
Fig. 6: Effect of ct & fct on reward over generations; $r = 0.3$, $gt = 10$.

group selection method. These results are further discussed and analyzed in Section 6.

6 Discussion

The results from our simulations suggest that the combination of tagging and group selection mechanisms can significantly promote the emergence of cooperation in the n-player Snowdrift game. While our findings align with prior research that highlights the importance of both mechanisms separately, we show that their combined integration leads to robust cooperation across a variety of parameters and conditions.

Figure 2 illustrates the cooperation levels across generations for each group in a simulation. Most groups are initially well-mixed, with neither cooperators nor defectors in the majority. Shortly thereafter, defectors begin to take over, with only one or two groups maintaining a majority of cooperators. A As long as other groups are mixed, defectors benefit at the expense of cooperators in those groups. Those defectors are selected by tournament selection, which causes the group to grow and eventually split. But once all of the mixed groups become



(a) Split Group to Empty.

(b) Split Group Evenly to Smallest.

Fig. 7: Cooperators over generations varying N_{Groups} and group selection method. $r = 0.35$, $ct = 1$, $gt = 10$.

devoid of cooperators, groups of defectors loses competitive advantage compared to any remaining group of cooperators. Beyond this point, e.g., generation 24 in Figure 2, groups of cooperators begin to proliferate and eventually replaces all groups of defectors in the population.

A parameter sweep over group split threshold gt reveals that smaller values of gt are much more conducive to cooperation in social dilemma games, as shown in Figure 4a. This differential between small and large group split thresholds is not unexpected; as groups grow larger, they begin to behave like a single population, which has been shown to not promote cooperation effectively [15].

As shown in Figure 5, cooperation emerges consistently for reasonable values of the cooperation threshold, ct. However, when ct is too large, it either slows the convergence toward total cooperation or prevents it altogether. This is to be expected as would result in many groups being unable to ever meet that threshold. When using a fractional threshold, however, even when $fct = 1.0$— meaning the entire group must cooperate— cooperation still emerges! This happens because the population is able to preserve fully cooperative groups.

Our final experiments examined the effects of varying the initial number of groups, N_{groups}, using two group selection methods: Algorithm 2, where groups split into empty ones by either locating an existing empty group or creating a new one, and Algorithm 3, which splits groups evenly and takes over existing groups. When using Algorithm 2, the SD game achieved high levels of cooperation for every value of N_{groups}, with a larger number of initial groups leading to slightly higher cooperation levels occurring in less generations. When using Algorithm 3, results show a notable decline in cooperator counts for smaller initial number of groups. Moreover, for a given value of N_{groups}, the proportion of cooperators tends to be lower with Algorithm 3. This difference perhaps stems from how the even splitting of groups in Algorithm 3 can only take over existing groups, whereas Algorithm 2 can create new groups and allows many groups of cooperators to grow simultaneously.

7 Conclusion and Future Work

We examined the effects of tag-based grouping, tournament selection, and group selection mechanisms on the emergence of cooperation in the multi-player Snowdrift game. Results show that combining these approaches engenders cooperative behavior in the Snowdrift game. Cooperation consistently emerges across a number of cost-benefit ratios, group split thresholds, and cooperation thresholds.

The following are some interesting research directions that we plan to pursue:

- We will compare the relative success of fitness proportionate selection Vs tournament selection in creating individual selection pressure.
- We will incorporate tag mutation, or random migration between groups, and observe concomitant effects on rate and success of cooperation emergence.
- We plan to evaluate a process for "voting to evict" individuals, where individuals in a group can vote on evicting one of their members from the group.
- Conversely, individuals may leave a group with subset of other group members. These approaches are complementary to, the current group splitting mechanism.
- Individuals may also decide to migrate to another group, but members of that group to vote to accept or deny the migrating individual from entering.

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