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Research article

Budget allocation and illegal fishing: a game theoretic approach

Maggie R. Sullens[1,2,*] **and Nina H. Fefferman**[1,2,3]

[1] Department of Mathematics, University of Tennessee, TN 37996, USA

[2] National Institute for Mathematical and Biological Synthesis, University of Tennessee, TN 37996, USA

[3] Department of Ecology and Evolutionary Biology, University of Tennessee, TN 37996, USA

* **Correspondence:** Email: sullens0098@gmail.com; Tel: +16783085933.

Abstract: Conservation efforts are under constant threat of failure due to poaching. Efforts to combat poaching may take a number of forms, but access to each form depends on resources, and access to these resources may depend on the success of previous efforts (e.g., monetary donations from supporters could directly combat poaching, but may be more effective if partially spent on recruiting additional supporters who then also donate). We adopted a mathematical framework with inspiration from the famous colonel blotto game to model the ongoing battle between conservationists and poachers. Focusing on a marine setting as a case study, players have budgets consisting of three types of resources: monetary, non-monetary, and supporters. The heterogeneous battlefields (laws, marine reserves, and community) reflect commonly employed conservation tactics meant to limit poaching. conservationists allocate resources to limit the success of poachers, while poachers allocate resources to overcome barriers implemented by conservationists. We assumed that no action can succeed without supporters, and thus whichever player wins over all the supporters in the community (i.e., the community battlefield), wins the game. We analyzed battlefield payoffs and player budget distributions to determine overall player success. We demonstrated how initially disadvantaged players may have an opportunity to win the game, although, we found that success in the first round can be most critical under certain scenarios. By framing the question in this way, we hope to provide additional tools for decision support to guide resource allocation, improving the efficacy of conservation efforts.

Keywords: conservation; policy; theoretical mathematics; human behavior; predictive modeling; decision-making

1. Introduction

Poaching is an ongoing issue threatening endangered species both across land and water habitats. Researchers stress the critical status of endangered animals and their bleak future if poaching continues [1–3]. Low leopard populations in Maputaland are a result of habitat loss, low food levels, and other factors, including poaching [4]. Additionally, overharvesting and poaching is contributing to the depletion of freshwater megafauna such as sturgeons, paddlefish, and the Cuban Crocodile [5]. Mathematical models provide insight for potential trajectories under current dynamics, different management strategies, or environmental change. The literature presents several models predicting future population levels. Some modeling techniques include statistical models [6], demographic models [7], and behavioral models [8], and have been used to give insightful information that helps target conservation efforts [9]. Reference [10] uses Leslie matrices and Monte Carlo simulations to examine uncertainty in population growth rate. Models can also provide comparisons for different management strategies or intensities, further providing insight for implementation [11, 12]. The work presented by [13] creates a model and preforms sensitivity analysis to conclude "protection of diverse coral communities with the presence, but not necessarily higher abundance, of thermally tolerant coral species and symbiont types, mitigation of additional anthropogenic impacts that affect coral–macroalgal competition, early coral life history stages, and coral survivorship, and protection of, and connectivity to, locations with oceanographic features that lead to lower thermal stress."

Endangered species are often hunted for cultural or religious reasons. Shark finning is illegal in many countries, but a large black market encourages poaching. The majority of fin imports go to Hong Kong and other areas of China, where they are used in culturally significant shark fin soup [14]. Dating back to the Ming dynasty, shark fin soup has been served as a status symbol. It initially served as a tribute to the emperor due to the risk involved in catching the shark, but later, animals known as being strong or fierce were additionally thought to strengthen whoever consumed them [15]. The cultural value of the fins create a market for poaching by having the potential to result in a large profit. Rhino horns also have an illegal market due to cultural demand. Vietnamese people value the horns for believed medical properties surrounding detoxification [16].

Several methods are implemented to reduce poaching. Laws or restrictions for hunting and trading are often put in place to penalize partakers and discourage participation. However, due to high demand and high prices, poaching still occurs. The US enacted the 2000 Shark Finning Prohibition Act, the 2009 Shark Conservation Act, and the Shark Fin Trade Elimination Act in 2017 to reduce finning by prohibiting the discarding of finned bodies, requiring sharks to be landed with fins intact, and prohibiting the sale and possession of fins [17]. However, the US accounts for only a small percentage of the trade and it is argued that a ban on shark fins would compromise the US's influence on other countries' likelihood to adopt conservation models [18].

Community outreach and education programs can help in a variety of ways. One being the allowance of community members to participate in research or volunteer work, which enables the local community to become invested in the conservation effort [19, 20]. Additionally, creating advertisements such as billboards, media coverage, and short videos can help inform the public of the critical condition of the species as well as the possible danger of consumption [21]. Often, local communities are not aware of the damage their actions are doing, making the education of adults and children critical [22]. Marine reserves restrict human interaction and are used to protect species by giving them a haven of recovery. They can put quotas on fishing, limit the number of vessels, limit fishing time, as well as many other restrictions [22]. These management strategies can be used simultaneously to give endangered species a chance at recovery.

Game theory is a mathematical technique that is used to study player interactions and predict outcomes that depend on the decisions of other player(s). Famously, game theory is used in finance, economics, military, politics, and other fields. One famous game is the Prisoner's Dilemma in which a players can choose to betray the other. Their choice to betray or be loyal to the other prisoner affects the outcome for them both [23]. Another famous game, and the one that serves as a basis for the methods in this paper, is the colonel blotto game in which two players allocate resources to different battlefields in the hopes of either winning the most battlefields or the most payoff. Battlefields can represent different platforms depending on the scenario in which the game is applied. The colonel blotto game has been used to explain social scenarios [24], network systems [25], and military strategy [26]. For military scenarios, battlefields can be land regions while for network systems, battlefields can be transmissions when looking at radio jamming attacks [27]. More recent work on the colonel blotto game includes the following: (1) analysis of multiplayer and Boolean versions [28], (2) equilibria analysis of the two-contestant generalized lottery colonel blotto games along with, under specified criteria, the generalized colonel blotto game [29, 30], (3) consideration of asymmetrical battlefields and player knowledge [31], and (4) optimal strategies formulation using polynomial-sized linear program [32].

Here, we use the colonel blotto game to address the issue of poaching where the players are conservationists and poachers. Players compete against each other by allocating a set number of resources to different areas or battlefields that contribute to the poachers' success at undermining conservation efforts and harvesting the species or the conservationists' success at restricting poaching. Extensions have been made to the basic format of the game to allow asymmetrical budgets [33]. Heterogeneous battlefields in which one battlefield is worth more than others is also considered. [34] proposes a solution to the case of both asymmetrical budgets and heterogeneous battlefields under certain conditions. We adopt this framework in our model with the addition of sub-battlefields and player budgets consisting of three resource types: monetary resources, non-monetary resources, and supporters. Monetary resources are money or economic resources, non-monetary resources are items such as boats, nets, and other physical equipment, and supporters are members of the community that either provide conservation support or a market for poachers to sell to. Players distribute each of their resource types by choosing from nine different strategies to three different battlefields: laws, marine reserves, and community. Each battlefield contributes to the overall payoff of the game in varying amounts, depending on the influence it has on the success of the players. To account for the different resource types in the budget, sub-battlefields corresponding to the resource types were built into each battlefield category with the weight of each sub-battlefield depending on its influence on its parent battlefield. The design of the nine strategies players choose was curated by identifying reasonable actions players may take in order to face their opponent. Additionally, institutional memory can be set to either "no memory", "memory of last round", or "memory of all previous rounds", which determines the information the players have when making a current strategy decision.

It is worth mentioning that another resource allocation game is multi-armed bandit (MAB) problems in which a single player must allocate resources to different projects to either receive initially high rewards or to potentially have a higher delayed reward [35]. However, these problems consist only of one player and not two players competing, differing from the game presented here.

In this paper, we approach the issue of poaching using the colonel blotto game framework in a novel approach by introducing a budget involving different resource types along with battlefields that correspond to impactful areas of conservation. Additionally, we add sub-battlefields within each battlefield to correspond to the different resource types and the influence each resource has on that battlefield. We consider how the community support of either conservation or the continuation of poaching affects the success of each player.

2. Materials and methods

The game theory model presented in this paper follows the framework of the famous Blotto game and explores how different strategies can affect the outcome of conservationists fighting against illegal fishing [36, 37]. Both conservationists and poachers have budgets consisting of resources that they allocate to different battlefields in the hopes of gaining an advantage over their opponent. The budget resources consist of monetary resources, non-monetary resources, and supporters while the battlefields are laws, marine reserves, and the community. The game consists of several rounds, with the budget for the proceeding round reflecting the outcome of the previous. A round refers to players allocating resources and the determination of who won each sub-battlefield based on who allocated more resources to that sub-battlefield. Although evolutionary game theory depends on previous game results, it combines population ecology and game theory and makes use of replicator equations for the evolution of strategies or traits [38, 39]. Here, we have the player budgets dependent on the previous round's payoff, which differs from the traditional evolutionary game theory approach.

Supporters, or the support of the community, is the driver of the game. Supporters for conservationists are community members that provide aid for conservation efforts by giving money or spreading positive attitudes for conservation. Supporters for poachers are community members that provide a market for poachers to sell to and encourage the continuation of poaching because of its cultural or social value. A player has the community's support when their supporter budget category consists of the majority of the community. The winner of the game is the player who wins the entire community's support. Once a player has the community's support, the other player either loses funding for conservation efforts or a market to sell into, making their efforts fruitless. Players can increase their number of supporters by allocating their resources effectively.

There are a few assumptions to the model that must be considered. First, the budgets of each player are known only to themselves, and therefore they do not know the budgets of their opponent. This differs from standard analyses of game-theoretic constructs, where players are typically assumed to know each other's budgets. However, our goal of this paper is to provide insight into real-world scenarios where players rarely have such knowledge. Second, the community is a fixed value, meaning that there is no flux of incoming or departing people. Resources such as boats, fishing gear, etc. are fixed across rounds, meaning that neither player is significantly investing in the creation of new equipment. Their goal is to use their equipment efficiently. Last, every player must start a game with nonzero values for each budget category.

Our model provides insight to how a budget can be allocated to give the best chance of winning the game.

Conservationists and poachers have different resources that collectively contribute to their goal. As described earlier, resources can be described as monetary, non-monetary, and supporters. We reflect the different resource categories through designing player budgets to reflect the three categories. The players' budgets are expressed as three-dimensional vectors $(\vec{C}, \vec{P})$ containing values for monetary, non-monetary, and supporters resources. The non-monetary category, containing resources such as ships, fishing gear, and equipment is a fixed value across rounds since it is assumed neither player is creating or destroying a significant amount of equipment. These resources are allocated based on the chosen strategy and have significant real-world applications, reflecting the resources available to actual conservationists and poachers, while also considering the potential rewards they offer. The supporters category is the proportion of the community that supports the efforts of the prospective player. Since every member of the community has to be accounted for, if conservationists have the support of 40% of the community, poachers have the remaining 60%. The monetary resources are dependent on how many supporters the player has. For conservationists, monetary resources come from supporter donations, tax collection, or other money collection methods. For poachers, monetary resources come from the market supporting the harvest of the illegal species. If the poachers do not have a market to sell to, they lose all their funding to continue with the illegal activity.

Equations (2.1) and (2.2), show how the budgets of each player is calculated. The components of the vectors are [monetary, non-monetary, supporters]. An example scenario is described with the following parameters. $c_1 = 0.4$, which means Conservationists have 40% of the community population as supporters. $a_1 = 8$, meaning each supporter contributes an average of \$8.00. Moreover, the poachers have the remaining 60% of the population, making $c_2 = 1 - c_1 = 0.6$. Each poacher supporter contributes an average of \$5.00, making $a_2 = 5$. $b_1 = 200$ and $b_2 = 150$, which are the non-monetary resources of conservationists and poachers, respectively.

$$\vec{C} = [a_1 c_1 * \text{population}, b_1, c_1 * \text{population}] \tag{2.1}$$

$$\vec{P} = [a_2 c_2 * \text{population}, b_2, c_2 * \text{population}] \tag{2.2}$$

After each round is won, the budgets are reevaluated based off of the payoff of the previous round, with the redistribution of the community being the driving factor.

Although there are many different areas where conservationists could make an impact, and different areas poachers must navigate in order to continue their practice, we focus on three major categories: laws, marine reserves, and community. Therefore, we designed the three battlefields to reflect this. Laws encompass policy creation and enforcement for the conservationists and encompasses policy repeal and ramification avoidance for poachers. Marine reserves include the creation and patrolling of areas deemed a marine reserve for conservationists, while for poachers, it includes police avoidance and the ability to operate effectively in the protected area. The community battlefield involves winning over supporters through campaigning, education, emphasis on traditions, or other outreach techniques. A payoff bank is set at the beginning of the game assigning each battlefield a percentage according to the contribution it has on the system. Ultimately, the player with the highest payoff wins the round. Equation (2.3) gives a vector representing a payoff distribution. The components correspond to laws, reserves, and community respectively. Thus, for example, if $p_1 = 0.15$, $p_2 = 0.3$, and $p_3 = 0.55$, then laws have a payoff of 15% of the payoff bank, reserves have 30% of the payoff bank, and community 55% of the payoff bank. It is a requirement that all the probabilities sum to one so the entirety of the payoff bank is accounted for without allotting more than exists.

$$\text{Payoff Distribution} = [p_1, p_2, p_3] \tag{2.3}$$

Within each battlefield, there are three sub-battlefields corresponding to the players' monetary, non-monetary, and supporter resources. This is to ensure budget categories are compared in compatible terms since, for example, is it not known how one non-monetary resource compares to one supporter. Additionally, one resource type may affect one battlefield category more than the other resource types. To account for this, each sub-battlefield contains a proportion of the battlefield's payoff corresponding to how much effect it would have on its parent battlefield. This creates the payoff matrix found in expression (2.4). The columns are the laws, reserves, and community battlefields while the rows are the monetary, non-monetary, and supporters sub-battlefields. Equation (2.5) gives the payoff matrix parameter values used for analysis. It assigns 55% of the laws battlefield's payoff to the monetary sub-battlefield, 20% to the non-monetary sub-battlefield, and 25% to the supporters sub-battlefield. Similar assignments are made for the reserves and community battlefields' payoffs. The monetary sub-battlefield holds the most for laws, non-monetary for the marine reserves sub-battlefield, and supporters for the community sub-battlefield. These could be altered to be scenario specific; however, we believe the distribution of each battlefield's payoff among its corresponding sub-battlefields presented in Eq (2.5) gives a reasonable and applicable scenario. It is required that the percentages of the sub-battlefields within its parent battlefield sum to one. Unlike player budgets, battlefield payoffs do not depend on previous rounds. The payoff matrix set at the beginning of the game remains fixed through the duration of the game.

$$\begin{array}{l} \\ \text{monetary} \\ \text{non-monetary} \\ \text{supporters} \end{array} \begin{array}{c} \begin{array}{ccc} \text{laws payoff} & \text{reserves payoff} & \text{community payoff} \end{array} \\ \begin{pmatrix} lm & rm & cm \\ ln & rn & cn \\ ls & rs & cs \end{pmatrix} \end{array} \tag{2.4}$$

$$\begin{array}{l} \\ \text{monetary} \\ \text{non-monetary} \\ \text{supporters} \end{array} \begin{array}{c} \begin{array}{ccc} \text{laws payoff} & \text{reserves payoff} & \text{community payoff} \end{array} \\ \begin{pmatrix} 0.55 & 0.3 & 0.3 \\ 0.2 & 0.5 & 0.1 \\ 0.25 & 0.2 & 0.6 \end{pmatrix} \end{array} \tag{2.5}$$

The implementation of the payoff matrix enables the battlefield to distribute it's payoff to both players according to the resources they allocated to it.

Both players have the ability to choose from nine strategies. They are listed below with supplementary examples as needed. Although the different strategies players can implement may exceed the ones listed here, we choose the following strategies by evaluating logical choices the players may make. We do not consider all possible options, since some allocations do not provide a viable strategy for reasonable players to make. Depending on the application of this model, some strategies can be removed or different strategies may be added. The players know the payoff distribution and may make decisions reflecting battlefield and sub-battlefield influences or payoff weights. Players may choose to allocate most of their resources to the battlefield or sub-battlefields containing the potential for the most payoff. Additionally, since the community battlefield ends the game once a player wins the community's support, players may choose to allocate more resources to the community battlefield. However, players may also attempt to predict what their opposition might do and allocate resources to battlefields they think their opposition might neglect. For example, they may anticipate their opposition allocating most resources to the highest paying battlefield or sub-battlefield and, therefore, allocate most of their resources to one or both the other battlefields or sub-battlefields. Table 1 summarizes the rationale behind the strategies listed along with categorizing them into three major categories: equitably dispersed, greedy, and opponent-conscious.

Table 1. This table summarizes the various allocation strategies categorized into three types: Equitably dispersed, greedy, and opponent-conscious. These categories illustrate the rationale behind players' strategic choices, such as targeting the battlefield with the highest payoff or anticipating the opponent's move.

	Strategy Names and Numbers	**Description**
Equitably Dispersed	(1) Even (6) Proportional Battlefields	Distributes resources systematically without strategically considering battlefield payoff or attempting to predict the opponents' move
Greedy	(2) Dominant Sub-battlefield (5) Dominant Battlefield (7) Community	Distributes resources in an attempt to win the highest advantage withoutanticipating the opponents' move
Opponent-conscious	(3) Proportional Non-dominant Sub-battlefields (4) Disproportional Non-dominant Sub-battlefields (8) Dominant Two Battlefields (9) Dominant and Community Battlefields	Distributes resources in an attempt to win the overall advantage by anticipating the opponents' move

1) **Even:** Allocate resources evenly across all battlefields and sub-battlefields.
2) **Dominant sub-battlefield:** Allocate all resources of a particular type to the sub-battlefield that contributes the most payoff for that battlefield. If the same sub-battlefield type contributes the most in two different battlefields, then the resources are split according to how much more one battlefield contributes than the other. If all three battlefields have the same top contributing sub-battlefields, distribute resources evenly across battlefields.

   Example: If the sub-battlefield in the battlefield laws that contains the most payoff contribution is monetary (0.55), and if the sub-battlefield in the reserves battlefield that has the most payoff contribution is monetary (0.5), then $\frac{0.55}{0.5} = 1.1$ more resources would go towards the laws battlefield. Thus, if the budget is 100, $1.1x + x = 100 \implies x = 100/2.2 = 47.619$ would go towards the laws battlefield and 52.381 would go to reserves battlefield. The category not accounted for is distributed across battlefields according to the contribution of the battlefields.

3) **Proportional non-dominant sub-battlefields:** Allocate resources of a particular type to the sub-battlefields that do not contribute the highest payoff. That way, they can win the most payoff from that battlefield without winning the highest paying sub-battlefield. If two battlefields share the same sub-battlefield as the second (third) most contributing, then split the resources proportionally to how much they contribute similar to the example in Strategy 2. If all three share the same second (third) contributing sub-battlefield, distribute evenly across battlefields. If one battlefield shares a second highest contributing sub-battlefield with a third contributing sub-battlefield in a different sub-battlefield, then all the resources go to the battlefield that has the second highest contributing sub-battlefield.
4) **Disproportional non-dominant sub-battlefields:** Allocate resources of a particular type to the sub-battlefields that do not contribute the most payoff, but if two battlefields share a second (third) sub-battlefield, then the majority (90–95%) goes the the battlefield that contributes the most while a minority (5–10%) goes to the other.
5) **Dominant battlefield:** If the payoff of the battlefield with the most payoff contribution is greater than the sum of the payoff contributions from the two remaining battlefields, then allocate all resources of all types to the battlefield that contributes the most. If the payoff of the battlefield with the most contribution is less than the sum of the contributions from the two remaining battlefields, then split all resources proportionally (same as in the example of Strategy 2) of all types to the two battlefields that do not contribute the most payoff.
6) **Proportional battlefields:** Distribute resources accordingly to how much payoff contribution the battlefield holds.

   Example: If the laws battlefield hold 15%, the reserves battlefield 30%, and the community battlefield 55%, then 15% of the monetary, non-Monetary, and supporter budgets would go to the laws battlefield, 30% of the monetary, non-monetary, and supporter budgets would go to the reserves battlefield, etc.

7) **Community:**Always allocate all resources to the community battlefield because the more supporters a player has, the larger their supporter and monetary budgets will be for the next round.
8) **Dominant two battlefields:** Allocate resources proportionally to the the top two battlefields with the highest payoff similarly to the method in the Strategy 2 example. If all battlefields have equal payoff, allocate resources evenly across battlefields.
9) **Dominant and community battlefields:** Allocate resources proportionally to the battlefield with the highest payoff and the community battlefield similarly to the method in the Strategy 2 example. If all battlefields have equal payoff, allocate resources evenly across battlefields.

If "no memory" is selected then, in every round, both players have equal probability of selecting any of the nine strategies. A scenario such as this represents a case where the turnover for either poachers, conservationists, or both correspond with the time frame of the rounds. This means that there is a new group of poachers or conservationists each round. Since there is no one left from the previous round to share which strategy was used, the current members know only the outcome, not the method, and therefore have to make a decision independent of the strategy chosen in the previous round.

If "memory of last round" is selected, then the results of the previous round influence the strategy decision. Similar to the "no memory" scenario, there could exist a turnover in at least one of the player categories. However, the turnover is longer than the time frame of a round and shorter than the time frame of two rounds. This means there exists people from the previous round to inform which strategy led them to the current results and current budgets. After one round, the information is lost as the people present during two rounds ago are replaced by new members. If the player won the previous round, then the player has a predetermined probability of adopting the previous strategy. Equation (2.6) illustrates how the probability of adoption is calculated.

$$P(\text{adopting previous strategy}) = \frac{\text{payoff won in previous round}}{\text{Payoff Bank}} \tag{2.6}$$

If the previous strategy is not adopted then, then players have equal probability of choosing any of the nine strategy, as they would if they had "no memory".

Last, if "memory of all previous rounds" is selected, then players remember the outcomes of all previous rounds, giving them the option of replaying the strategy that awarded them the highest payoff. A case of "memory of all previous rounds" represents a scenario where poacher and Conservationist members maintain excellent records of previous strategies used and the corresponding results for current members to refer to when approaching a new round. The probability of adopting the most successful previous strategy is found using Eq (2.6). No matter which institutional memory scenario is chosen, the game is over when one player wins the support of the entirety of the community.

A game is made up of one or more rounds in which each player chooses a strategy and allocates their budget. The outcome determines who won the round, or if one player has collected the entire community as supporters, who won the game. If the community is still split between players, the budgets for the next round are determined by the outcome of the previous round. The winner of the round is the player with the highest awarded payoff.

3. Results

To understand the outcome of the game and potentially aid in decision making, the results from a single round played with budgets adopting extreme cases are compared. Extreme cases are where players have a budget containing a large amount of one resource and a minimal amount of the other two. The values selected as the large and small amounts are arbitrary and could have been chosen differently as long as they are sufficiently large or small, respectively.

The different extreme player budget cases account for different applicable scenarios. For example, if conservationists have high monetary resources and poachers have high supporters, then this could represent a case where poaching has cultural or religious value, but a portion of taxes go toward methods to reducing illegal fishing. An example of this is the importance of sharks in Chinese and Hawaiian cultures. For the Chinese, it originated as a delicacy reserved for the emperor or the wealthy, while in Hawaii, sharks are rarely eaten, but hold religious significance such as being influential spirits [14].

If conservationists have high supporters and poachers have high monetary resources, then it could mean that conservationists have a lot of supporters, but do not have effective fund raising methods or governmental aid. Community conserved areas (CCAs) are areas that are protected via community based rules and regulations and are most common among indigenous or rural communities [40]. Moreover, poachers are selling the illegal species at an inflated price so not many customers are required. Whale sharks are a highly conserved species of shark with consequences such as high fees and imprisonment for poaching or market participation, but areas such as Indonesia still have issues with poaching due to the high price of the fish [41].

We are assuming that if either player has high non-monetary resources, it is due to a previous acquirement of the resources. Non-monetary resources are fixed throughout the game meaning that a significant amount of equipment or other non-monetary resources is not gained or lost throughout the game.

Additional to single round results with extreme player budgets, heatmaps of full game outcomes give results of player wins according to how many rounds the game consists of and the institutional memory setting. Together, these analyses provide a basis for predicting player outcomes and strategy suggestions for desirable results.

In order to predict a player's outcome after one round of play, each player's possible strategies are played against all the other player's strategies and the payoff distribution is depicted by heatmaps. Figure 1 provides the distributions for each player in the extreme scenarios. That is, when a player has a large amount of one resource and minimal amount of the other two. The values chosen are arbitrary but capture the desired extreme scenario properties. Since all people in the community must be accounted for, if one player has the majority of the population as supporters, then the other player must have the minority. This reduces the number of combinations significantly. To determine the winner, we calculate the difference between the conservationists' and poachers' payoffs, with a positive value indicating a conservationists win and a negative value indicating a poachers win. Additionally, the battlefields' payoffs are distributed among its sub-battlefields according to the distribution outlined in Eq (2.5). Box plots of single round comparisons can be found in the Appendix (Figures A1–A12) and provide more accessible insight into the distribution statistics, particularly median values. In addition to the consideration of budget extremes, different battlefield payoff distributions are considered, including even battlefield payoffs, the majority going to the community battlefield with the resources battlefield having twice the payoff as the laws battlefield, and the majority going to the community battlefield with the resources battlefield having half the payoff as the laws battlefield. The community battlefield carries the most contribution in the non-equal battlefield payoff scenarios due to the community being the driving factor for both the game termination and the next round monetary budget. The Payoff Bank value is 100 and the community population is 100 persons.

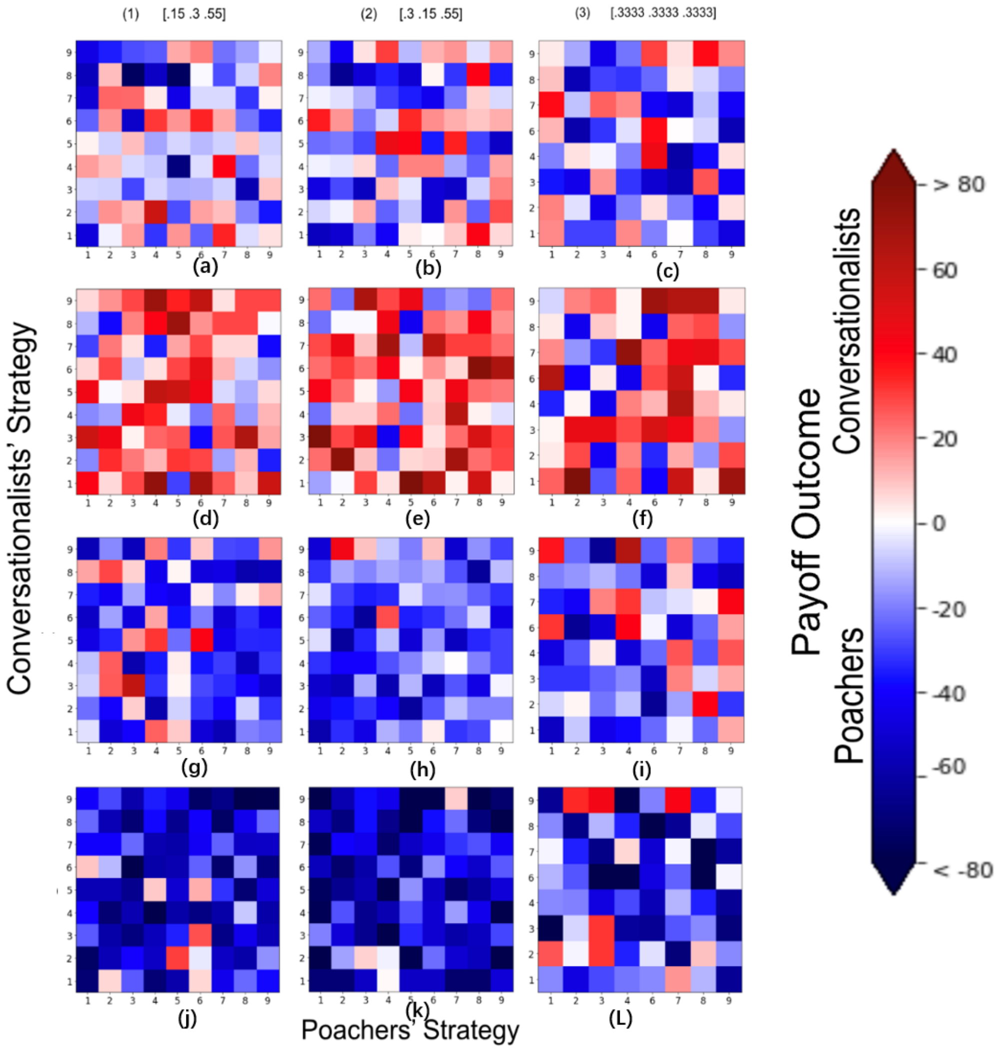

Figure 1. Column (1) represents when battlefield payoff distribution is [Laws, Marine Reserves, Community]=[0.15 0.3 0.55]. Column (2) represents when battlefield payoff distribution is [Laws, Marine Reserves, Community]=[0.3 0.15 0.55]. Column (3) represents when battlefield payoff distribution is even. That is, [Laws, Marine Reserves, Community]=[0.3333 0.3333 0.3333]. For (a)–(f), the budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)], and the budget for poachers is [High, Low, Low]=[20*(People), 10, 0.1*(Population)] in (a)–(c), and [Low, High, Low]=[1*(People), 200, 0.1*(Population)] in (d)–(f). For (g)–(L), the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9(Population)], and the budget for conservationists is [High, Low, Low]=[20*(People), 10, 0.1*(Population)] in (g)–(i), and [Low, High, Low]=[1*(People), 200, 0.1*(Population)] in (j)–(L). The legend refers to the difference between the conservationists' and poachers' payoffs, with positive values indicating a Conservationist win and negative values indicating a poacher win.

Assuming the players do not know the budgets of the other player but do know the battlefield payoff distribution, then we can analyze which strategies would give optimal results for each. Figure

1(a),(d),(g),(j) uses battlefield payoff distribution [Laws, Marine Reserves, Community]=[0.15 0.3 0.55]. If conservationists have high supporters, then they should either play the even, proportional battlefields, dominant two battlefields, or dominant and community battlefields strategy with even and proportional battlefields having the potential for the highest payoff. Moreover, if poachers have high supporters, they should also play either the even, proportional battlefields, dominant two battlefields, or dominant and community battlefields strategy. If conservationists have high monetary resources, poachers have the advantage, but conservationists should play the proportional battlefields strategy to have the highest change of winning the round. If poachers have high monetary resources, they are at a disadvantage but should play proportional battlefields, dominant two battlefields, or dominant and community battlefields strategy to have the highest change of winning the most payoff. If conservationists have high non-monetary resources, then they should play either the even or proportional battlefields strategy to have the potential for the highest payoff and the highest probability of winning the game. If poachers have high non-monetary resources, they should play either the even, proportional battlefields, dominant two battlefields, or dominant and community battlefields strategy to have the highest chance of winning the most payoff.

In the scenario that the battlefield payoff distribution is [Laws, Marine Reserves, Community]=[0.3 0.15 0.55] (Figure 1(b),(e),(h),(k)), then if conservationists have high supporters, they should either play the even, proportional battlefields, dominant two battlefields, or dominant and community battlefields strategy to ensure winning the round, while if poachers have high supporters, then they should either choose the even, dominant two battlefields, or dominant and community battlefields strategy. If conservationists have high monetary resources, then the proportional battlefields strategy gives them the highest chance of winning, while if poachers have high monetary resources, then the proportional battlefields, dominant two battlefields, and dominant and community battlefields strategies give the highest chance of winning the round. If conservationists have high non-monetary resources, then the even and proportional battlefields strategies give the highest chance of winning the round and the potential for the highest payoff. If poachers have high non-monetary resources, then similarly, the even and proportional battlefields strategies would give them the highest chance if winning the round.

Last, if the battlefield payoff is equally distributed ([Laws, Marine Reserves, Community]=[0.3333 0.3333 0.3333]) (Figure 1(c),(f),(i),(L)), then the dominant battlefield strategy cannot be played due to constraints on that strategy. If conservationists have high supporters, then the even, proportional battlefields, dominant two battlefields, or dominant and community battlefields strategies give the highest chance of winning the round along with the highest potential payoff. If poachers have high supporters, then the even, dominant two battlefields, or dominant and community battlefields strategies will almost guarantee poachers win the round. Otherwise, the poachers have only high chance of winning the round. For both players, if they have high monetary resources, then the even, dominant two battlefields, or dominant and community battlefields strategies will give them the highest chance of winning the most payoff. Additionally, for both players, if they have high non-monetary resources, then the even, proportional battlefields, dominant two battlefields, or dominant and community battlefields strategies give the highest chance of winning the round.

In order to analyze how different institutional memory and the number of rounds affect the winner of the game, Figure 2 presents heatmaps of win frequency based on institutional memory and the number of rounds in the game. Histograms of player win distribution and number of rounds can be found in the Appendix (Figures A13–A21). Each scenario runs 1000 games and plots which player won the most rounds and indicates how much. The negative values indicate poachers winning more games than conservationists while positive values indicate conservationists winning more games than poachers. Larger relative numbers show a larger difference in the number of games won. The same three different battlefield payoff distributions used in Figure 1 are considered in Figures 2 comparisons. That is, one where the the community battlefield holds over half of the payoff bank while the non-monetary battlefield holds twice as much as the monetary battlefield, another where the monetary and non-monetary battlefield switch payoffs, and one where all battlefields have the same distribution. Additionally, the extreme cases of the players' budgets are compared.

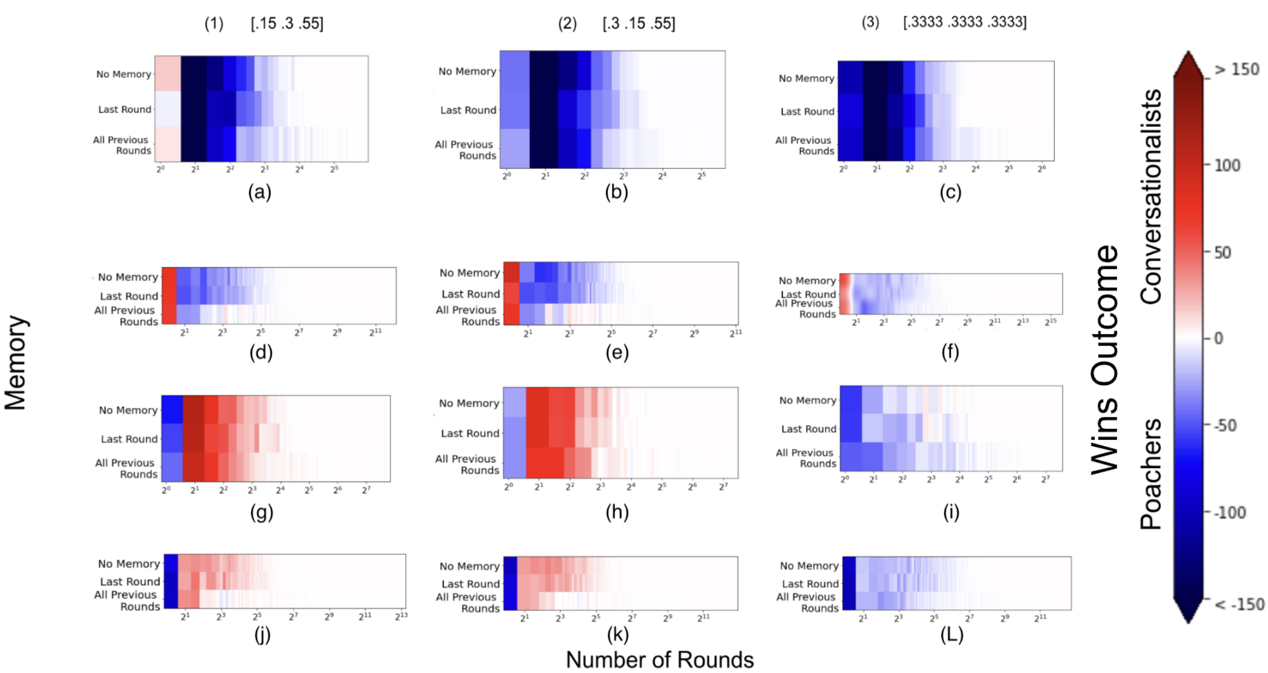

Figure 2. Column (1) represents when battlefield payoff distribution is [Laws, Marine Reserves, Community]=[0.15 0.3 0.55]. Column (2) represents when battlefield payoff distribution is [Laws, Marine Reserves, Community]=[0.3 0.15 0.55]. Column (3) represents when battlefield payoff distribution is even. That is, [Laws, Marine Reserves, Community]=[0.3333 0.3333 0.3333]. (a)–(c) is when the budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)] and the budget for poachers is [High, Low, Low]=[20*(People), 10, 0.1*(Population)]. (d)–(f) is when the budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)] and the budget for poachers is [Low, High, Low]=[1*(People), 200, 0.1*(Population)]. (g)–(i) is when the budget for conservationists is [High, Low, Low]=[20*(People), 10, 0.1(Population)] and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)]. (j)–(L) is when the budget for conservationists is [Low, High, Low]=[1*(People), 200, 0.1(Population)] and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)]. Negative values represent poachers winning more games and positive values represent conservationists winning more rounds.

Figure 2(a),(d),(g),(j) shows when the battlefield payoff vector is [Laws, Marine Reserves, Community]=[0.15 0.30 0.55]. Across memory cases, whoever holds high supporters has the highest chance winning the game if few rounds occur. However, as rounds accumulate, the game favors the opposing player. This makes the first few rounds imperative to the player with low supporters. If conservationists have high supporters, then they have the most advantage if the game ends in one round with the memory of all previous rounds scenario giving the most advantage. Players must choose a strategy that would allow the game to continue to a favorable number of rounds based on their resource distribution. Figure 1(a),(d),(g),(j) reveals which strategies could give the high supporter player the best chance of winning by ending the game in few rounds.

The battlefield payoff vector [Laws, Marine Reserves, Community]=[0.3 0.15 0.55] is shown in Figure 2(b),(e),(h),(k). Again, across memory cases, the player with high supporters has an advantage when round numbers is low. As rounds accumulate, the player with low supporters is favored. If poachers have high monetary resources and conservationists have high supporters, then the poachers only have an advantage with games lasting around two rounds. Figure 1(b),(e),(h),(k) reveals which strategies could give the high supporter player the best chance of winning by ending the game in few rounds.

Figure 2(c),(f),(i),(L) shows scenarios when the battlefields have an even distribution ([Laws, Marine Reserves, Community]=[0.3333 0.3333 0.3333]). poachers have a significant advantage across memory cases with the ability to ensure winning the game if they have high supporters and conservationists having high non-monetary resources. Otherwise, the first one or two rounds is the most critical for conservationists. When conservationists have high supporters and poachers have high non-monetary resources, then conservationists have the highest likelihood of winning the game across memory cases. However, memory of the last round has the most potential for a favorable outcome. Figure 1(c),(f),(i),(L) provides valuable information for strategy selection in an even battlefield scenario.

4. Discussion, future work, and conclusions

Our goal of this paper is to give insightful information on which strategies could give the desired results relating to illegal fishing using a game theoretic method following the famous colonel blotto game framework. Although in the results section, we consider what each player could play to potentially improve their chances of winning the game, here we consider only what would improve the conservationists chances of winning and reducing illegal fishing practices. We shift to a bias of conservationists since our goal is to reduce illegal fishing, bringing concentration to the decisions conservationists can make to prevail over the poachers. The different budget distribution, payoff distributions, and institutional memory scenarios used in the results sections are also used here. The different memory cases did not have a large effect on the winner distribution, showing that the book keeping or institutional turnover does not impact the long term winner. However, memory does have a large impact of the duration of the game, allowing some games to reach over 4000 rounds. This is due to players repeatedly playing strategies that gave them the most success, so it takes longer for the winner to gain precedence over the other player. Additionally, this could mean that poachers and conservationists are locked in an impasse for such an extended period of time, that it would be unreasonable to deem one a winner since other factors such as the demise of the species, climate change, or societal changes may occur to invalidate the time frame.

The game ends when one player wins the full support of the community. In the model, this is done by one player obtaining all persons as supporters. In application, this means that overall, the community supports either conservationists or poachers so drastically that the opposition does not either have the funds or the market to continue their effort. In other words, it is either not feasible for conservationists to continue to attempt to conserve the species or it is not economic for poachers to continue the illegal activity.

The most critical battlefield is the community battlefield since the game is over when a player wins the support of the community. However, a player can still win the game even if they start with a low number of supporters. Figure 2(g),(j),(h),(k) show that conservationists can win the game even though they start with a small number of supporters. This shows that with other resources, players can accumulate supporters.

Regardless of institutional memory, when the battlefield payoff distribution emphasizes the community battlefield, if conservationists have high monetary resources, then they would most likely prevail over the poachers if more than one round occurs. This occurs even with few supporters. Tactics could be used that follow strategies such as the proportional battlefields strategy (Figure 1(a),(d),(g),(j),(b),(e),(h),(k)) that would allocate the majority of all resources to the community battlefield. If conservationists have high non-monetary resources the even or proportional battlefield strategy would give the best chance of extending the rivalry past one round, hence giving conservationists an edge. The even strategy allocates all resources evenly across battlefields. If conservationists have a high number of supporters, they have the highest chance of winning the game if few rounds are played and the even, proportional battlefields, dominant two battlefields, and dominant and community battlefields strategies will give them the highest chance of succeeding in their conservation goals.

The bleakest case for conservationists is when the battlefields have an even payoff distribution, which can represent a case where laws, marine reserves, and community support are interconnected in such a way that one category does not have significantly more impact on the system as a whole. For example, the community promotes laws for the reduction of poaching along with the creation of marine reserves, laws are made to protect marine reserves, and the public being able to enjoy protected areas further recruits supporters. Regardless of memory, if conservationists have a high number of supporters, then they have the highest, or only, chance of reducing poaching when the rivalry consists of one round, meaning allocating resources aligning with the even, proportional battlefields, dominant two battlefields, or dominant and community battlefields strategies (Figure 1(c),(f)) would give the highest chance of conservationists reaching their conservation goals. If conservationists have high monetary resources, they have the highest chance of reducing poaching if less than two rounds occur. The even, dominant two battlefields, or dominant and community battlefields strategy should be implemented (Figure 1(i)). If conservationists have high non-monetary resources, then they will fail to conserve the species.

We present information as to which strategies have potential for resulting in desirable outcomes based on the budget of each player. Conversation groups can refer to the results here in choosing the best allocation of their resources according to their resource budget distribution and with supplementation from their region's emphasized operations. For example, a study was done on the Misool and Kofiau islands comparing the community's attitude before and after MPA education and outreach programs. It was found that after the programs, more people had positive attitudes towards MPAs [42]. Therefore, for an area such as this, the community battlefield would contribute a large payoff, and budget allocation should reflect that.

In this paper, we focus on battlefields corresponding to laws, marine reserves, and community influence. However, the methods presented here could be extended to include other battlefield categories such as patrolling or enforcement. Although, the categories in this paper cover the enforcement of the laws and reserved areas, creating a new battlefield could emphasize the effort it would take. For example, in Mexico, intensive beach management including beach patrolling has had a significant positive impact on sea turtle nesting sites [43].

Additionally, players have a budget consisting of monetary, non-monetary, and supporter resources. The non-monetary resources could be broken into more specific categories such as boats and nets. This could provide more information about if targeting a specific equipment category could impact conservation efforts. Also, allowing new equipment to be made or destroyed could change the dynamics of the game. However, equipment such as boats can vary greatly. For example, in the Philippines, fishing boats can be municipal or commercial boats, which each consist of subcategories, furthering the difference between the different types [44]. Standardizing across the different equipment would have to occur for proper comparisons.

The time it takes for allocation to different battlefields to have an effect on conservation efforts would also be a valuable addition. Laws can be made fairly quickly, while the time it takes to change the attitude of the community may take considerably longer. Within community education programs, methods such as surveys should be used throughout the program such as when insecticide-treated bed nets were implemented in Kenya. Surveys revealed mothers' concerns and gave researchers potential areas for consideration and targeted education [45]. Knowing the community is key when implementing an outreach program, but takes time and consideration.

Although this model is made specifically for marine applications, it could easily be adapted to different conservation scenarios. Elephant and Rhino poaching in Africa is a large issue due to ivory trade. Elephant poaching has been on an upward trend, and although elephants do not currently have the highest level of protection, budget allocation could help plan which strategy would result in most favorable results for conservation [46]. Additionally, rhino conservation face obstacles such as "inadequate funding and law enforcement, weak policy and legal frameworks, and disgruntled and marginalized communities who antagonize conservation efforts, illegal harvesting and international trade, and habitat fragmentation and loss" [47]. Considering different budget allocation strategies would help conservationists make a more informed approach to give the rhino a better chance at survival.

In summary, we implement the famous colonel blotto game to present a framework for capturing the effect resource allocation by conservationists and poachers under varying budget, payoff, and institutional memory scenarios have. We found that even if a player starts disadvantaged, they can succeed in their conservation or poaching goals. For example, if Conservationist starts with limited supporter resources, when the community battlefield has the most contribution, they can still succeed in conserving the targeted species. This proves useful in encouraging conservationists to persist in their efforts, even in bleak circumstances. Additionally, with some budget distributions, the first few rounds are crucial if the player hopes to succeed. This result suggests that players in this scenario may find success by focusing their efforts in the early rounds, but if the game continues, their efforts may no longer be a worthwhile endeavor. Last, if battlefields have an even payoff distribution, the conservationists have an unfortunately low probability of prevailing over the poachers, especially as the game consists of more rounds. This could be because when battlefields have equal payoff and conservationists either have high monetary or supporter resources, they can win over enough supporters at the beginning to win the game due to either not having to win over much more of the community to have full support or to have enough monetary resources to effectively promote their cause. However, as the rounds progress and poachers win supporters over, conservationists lose their advantage and are unable to gain it back since the community battlefield does not hold the majority payoff. conservationists may find value in anticipating their potential downfall, enabling them to either reconsider their efforts not worthwhile or seek external support to shift the game's dynamics. Ultimately, the combination of the players' initial budgets and battlefield payoff distribution is what enables one player to have an advantage over their opponent.

Memory does not have a sizable affect on who wins the round, but can affect the duration of the rivalry with "memory of all previous rounds" producing the longest encounters. Overall, we present results than could aid conservationists in choosing strategies to fight against poachers by giving different scenarios of battlefield payoff distributions, institutional memory, and player budget distributions. Although specific case-by-case information is vital to every conservation effort, the model presented here can help make a more informed decision.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare there are no conflicts of interest.

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Appendix

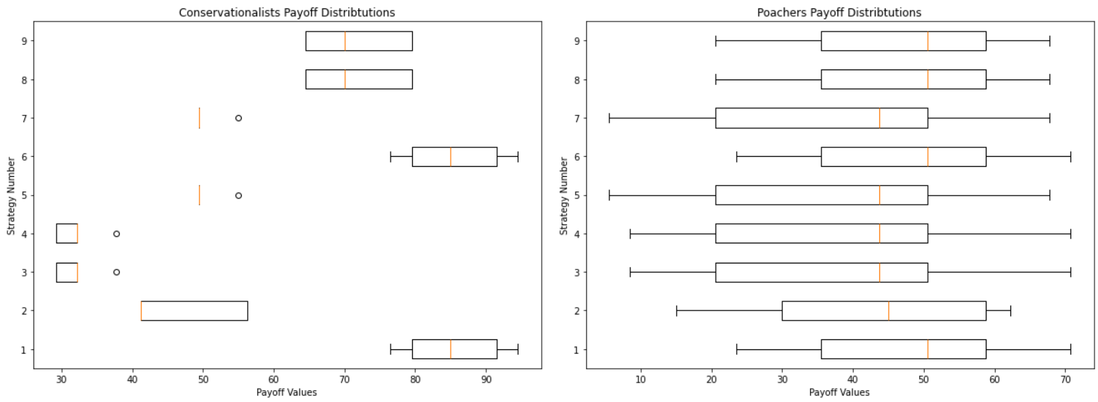


Figure A1. The battlefield payoff vector is [Laws, Marine Reserves, Community]=[0.15 0.3 0.55], meaning that the community contributed the most with more than half of the payoff bank while the marine reserves contributed a moderate amount and laws contributed the least. The resources for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)] while the resources for poachers is [Low, High, Low]=[1*(People), 200, 0.1*(Population)]. If conservationists play strategies 1, 6, 8, or 9, they will win regardless of which strategy poachers play. However, strategies 1 and 6 have a higher median payoff. No strategy will guarantee poachers will win, but strategies 1, 6, 8, and 9 have relatively the same median payoff that would win the round.

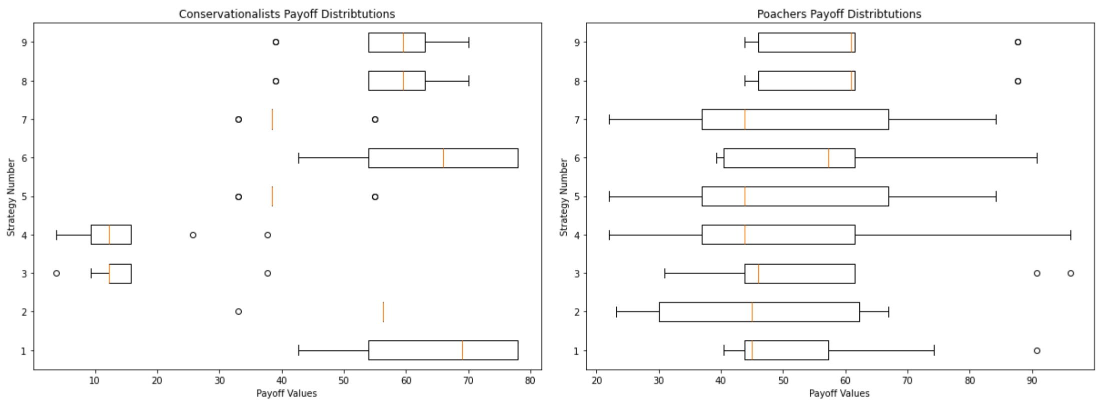


Figure A2. The battlefield payoff vector is [Laws, Marine Reserves, Community]=[0.15 0.3 0.55], meaning that the community contributed the most with more than half of the payoff bank while the marine reserves contributed a moderate amount and laws contributed the least. The resources for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)] while the resources for poachers is [High, Low, Low]=[20*(People), 10, 0.1*(Population)]. If conservationists play strategies 2, 6, 8, or 9, they have a high chance of winning the most payoff. However, strategies 1 has the highest median payoff. No strategy will guarantee poachers will win, but strategies 8 and 9 have the same median payoff that would win the round.

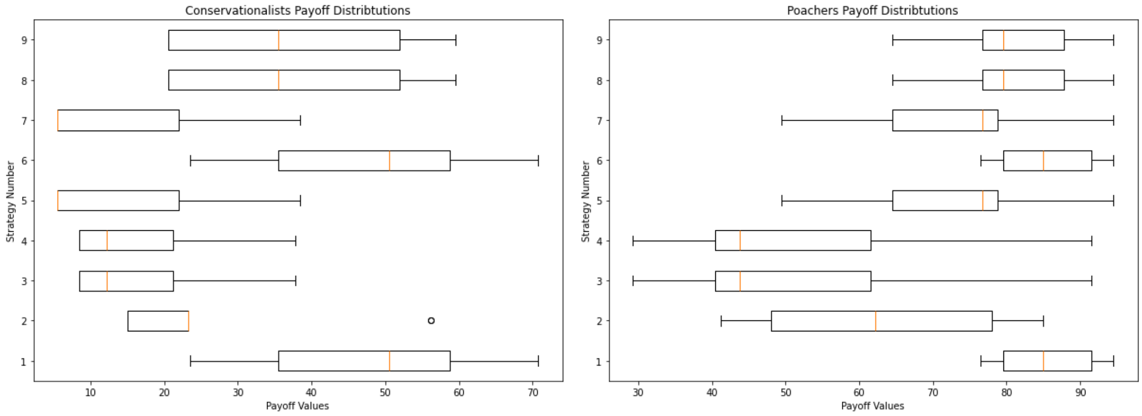


Figure A3. The battlefield payoff vector is [Laws, Marine Reserves, Community]=[0.15 0.3 0.55], meaning that the community contributed the most with more than half of the payoff bank while the marine reserves contributed a moderate amount and laws contributed the least. The resources for conservationists is [Low, High, Low]=[1*(People), 200, 0.1(Population)] while the resources for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)]. No strategy will guarantee conservationists will win, but strategies 1 and 6 have the approximately the same median payoff that would win the round. If poachers play strategies 1, 6, 8, or 9, they will win the most payoff. However, strategies 1 and 6 has the highest median payoff.

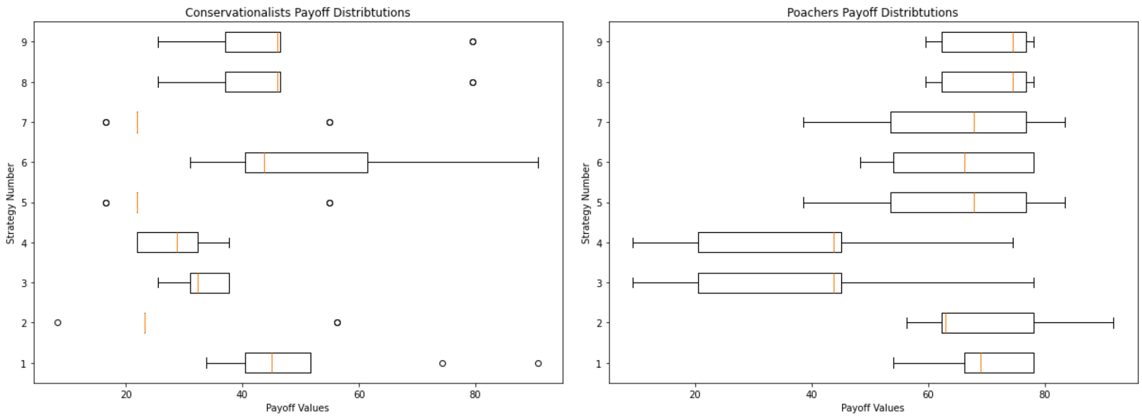


Figure A4. The battlefield payoff vector is [Laws, Marine Reserves, Community]=[0.15 0.3 0.55], meaning that the community contributed the most with more than half of the payoff bank while the marine reserves contributed a moderate amount and laws contributed the least. The resources for conservationists is [High, Low, Low]=[20*(People), 10, 0.1(Population) while the resources for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)]. No strategy will guarantee conservationists will win. However, strategy 6 has the highest chance of giving conservationists a winning payoff. If poachers play strategies 1, 2, 8, or 9, they will win the most payoff. However, strategies 8 and 9 has the highest median payoff.

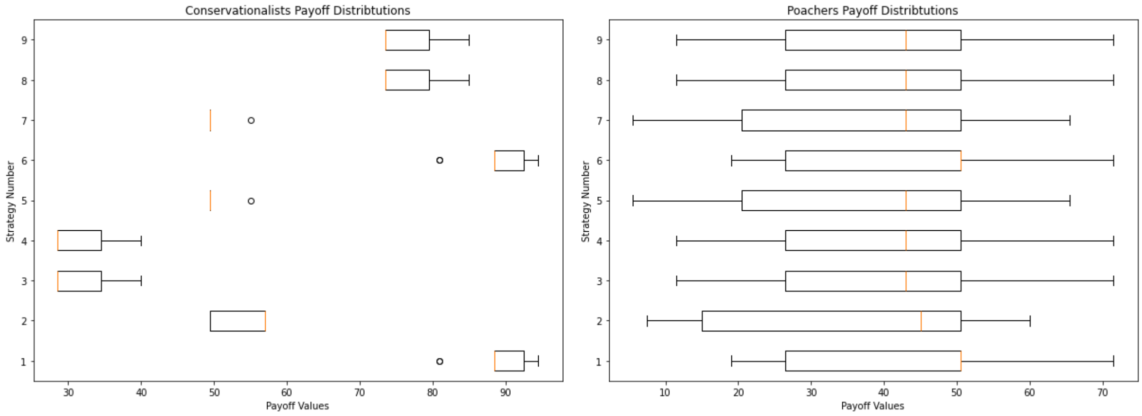


Figure A5. The battlefield payoff vector is [Laws, Marine Reserves, Community]=[0.3 0.15 0.55], meaning that the community contributed the most with more than half of the payoff bank while the laws contributed a moderate amount and marine reserves contributed the least. The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)] and the budget for poachers is [Low, High, Low]=[1*(People), 200, 0.1*(Population)]. If conservationists play strategies 1, 6, 8, or 9, they will win the most payoff. However, strategies 1 and 6 has the highest median payoff. No strategy will guarantee poachers will win. However, strategies 1 and 6 have the highest median payoff that wins the round.

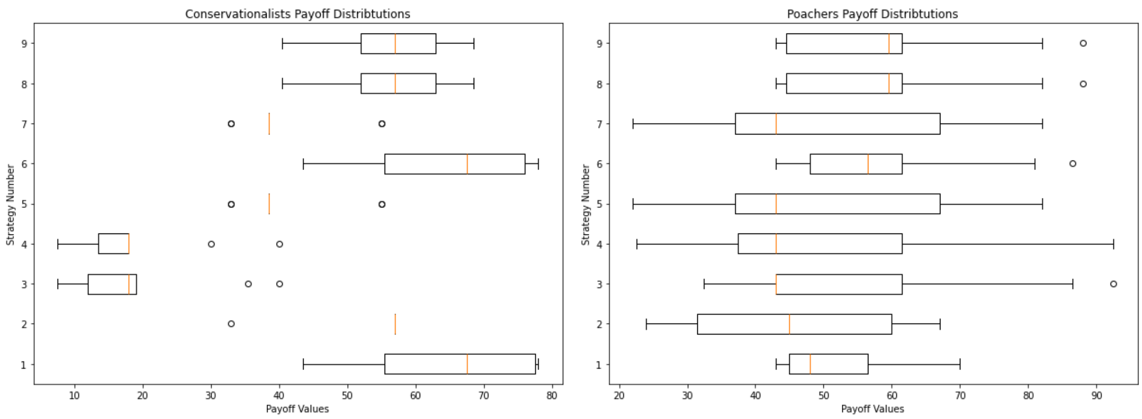


Figure A6. The battlefield payoff vector is [Laws, Marine Reserves, Community]=[0.3 0.15 0.55], meaning that the community contributed the most with more than half of the payoff bank while the laws contributed a moderate amount and marine reserves contributed the least. The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)] and the budget for poachers is [High, Low, Low]=[20*(People), 10, 0.1*(Population)]. No strategy will guarantee conservationists will win. However, strategies 1, 2, 6, 8, and 9 have the highest chance of giving conservationists a winning payoff. Additionally, no strategy will guarantee that poachers will win the round, but strategies 8 and 9 give poachers the highest chance of winning and the highest median payoff.

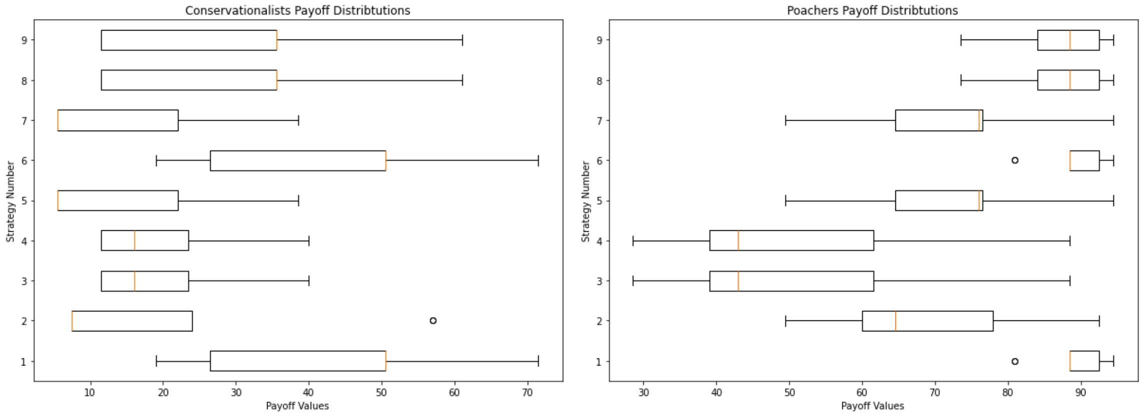


Figure A7. The battlefield payoff vector is [Laws, Marine Reserves, Community]=[0.3 0.15 0.55], meaning that the community contributed the most with more than half of the payoff bank while the laws contributed a moderate amount and marine reserves contributed the least. The budget for conservationists is [Low, High, Low]=[1*(People), 200, 0.1(Population)] and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)]. No strategy will guarantee conservationists will win. However, strategies 1 and 6 has the highest chance of giving conservationists a winning payoff and the highest median payoff. If poachers play strategies 1, 6, 8, or 9, they will win the most payoff.

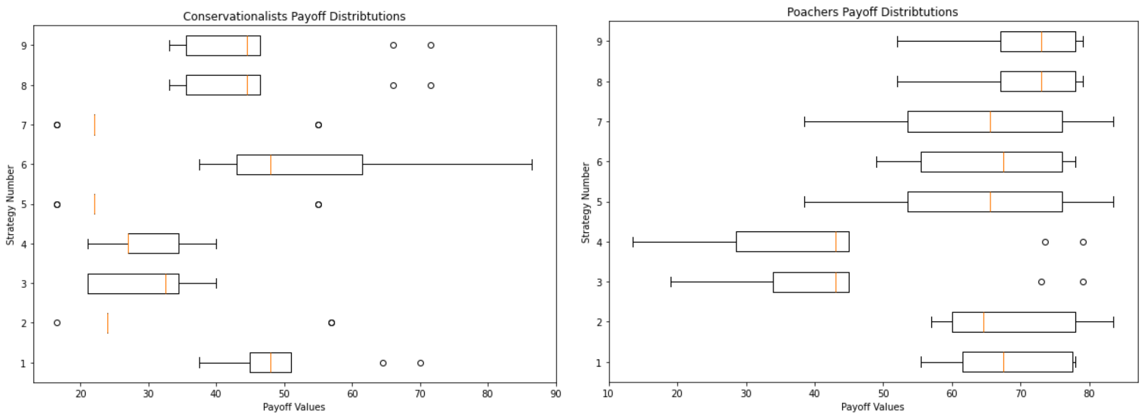


Figure A8. The battlefield payoff vector is [Laws, Marine Reserves, Community]=[0.3 0.15 0.55], meaning that the community contributed the most with more than half of the payoff bank while the laws contributed a moderate amount and marine reserves contributed the least. The budget for conservationists is [High, Low, Low]=[20*(People), 10, 0.1(Population)] and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)]. No strategy will guarantee conservationists will win. However, strategy 6 has the highest chance of giving conservationists a winning payoff. If poachers play strategies 1, 2, 8, or 9, they will win the most payoff. However, strategies 8 and 9 has the highest median payoff.

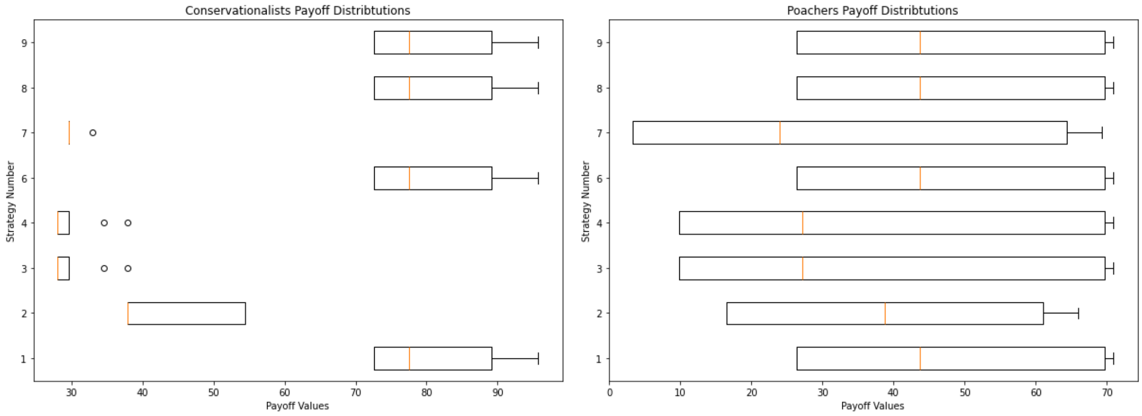


Figure A9. The battlefield payoff vector is [Laws, Marine Reserves, Community]=[0.3333 0.3333 0.3333], meaning that all battlefields contribute equal amounts of the Payoff Bank. Strategy 5 has been omitted due to the inability to pay it with the case of equal battlefields.The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)] and the budget for poachers: [Low, High, Low]=[1*(People), 200, 0.1*(Population)]. If conservationists play strategies 1, 6, 8, or 9, they will win the most payoff with all having the same median payoff. No strategy will guarantee poachers will win. However, strategies 1, 6, 8, and 9 has the highest chance of giving poachers a winning payoff.

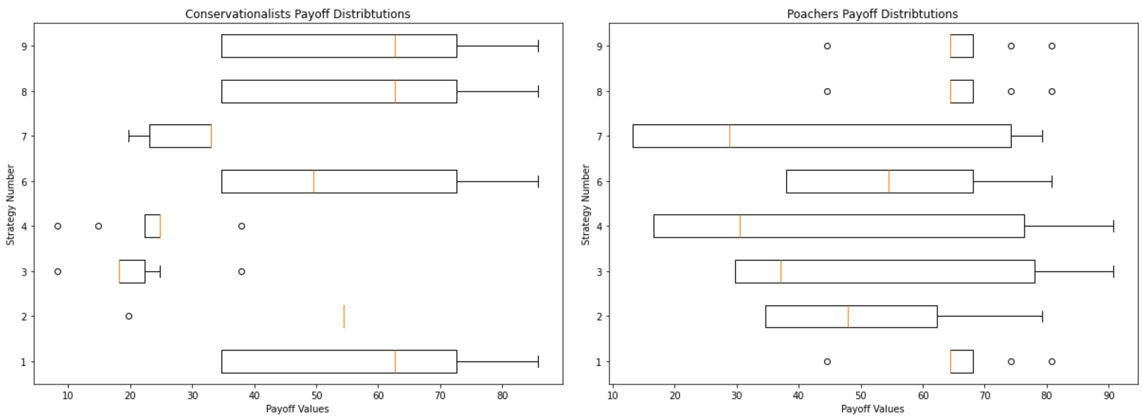


Figure A10. The battlefield payoff vector is [Laws, Marine Reserves, Community]=[0.3333 0.3333 0.3333], meaning that all battlefields contribute equal amounts of the Payoff Bank. Strategy 5 has been omitted due to the inability to pay it with the case of equal battlefields. The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)] and the budget for poachers is [High, Low, Low]=[20*(People), 10, 0.1*(Population)]. No strategy will guarantee conservationists will win. However, strategies 1, 6, 8, and 9 have the highest chance of giving conservationists a winning payoff. Additionally, no strategy will guarantee poachers will win the round, but strategies 1, 8 and 9 give poachers a very high chance of winning and the highest median payoff.

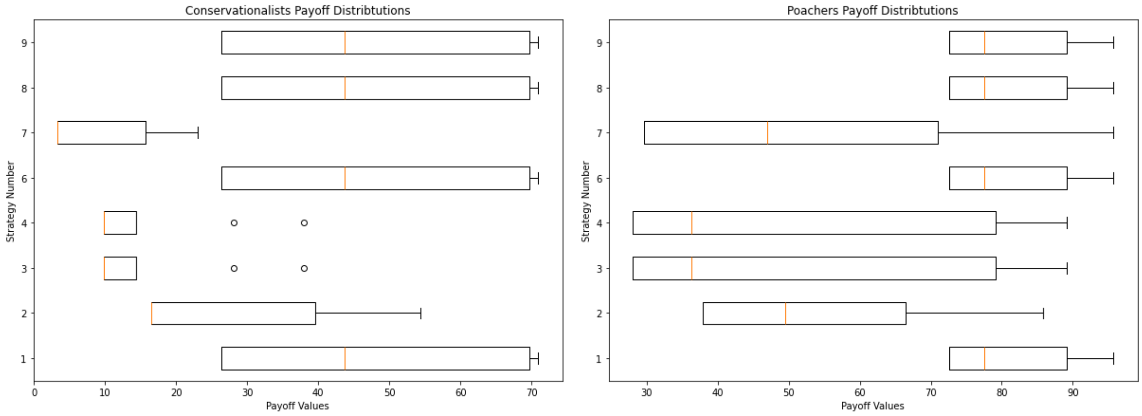


Figure A11. The battlefield payoff vector is [Laws, Marine Reserves, Community]=[0.3333 0.3333 0.3333], meaning that all battlefields contribute equal amounts of the Payoff Bank. Strategy 5 has been omitted due to the inability to pay it with the case of equal battlefields. The budget for conservationists is [Low, High, Low]=[1*(People), 200, 0.1(Population)] and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)]. No strategy will guarantee conservationists will win. However, strategies 1, 6, 8, and 9 have the highest chance of giving conservationists a winning payoff. If poachers play strategies 1, 6, 8, or 9 they will win the most payoff with all having the same median payoff.

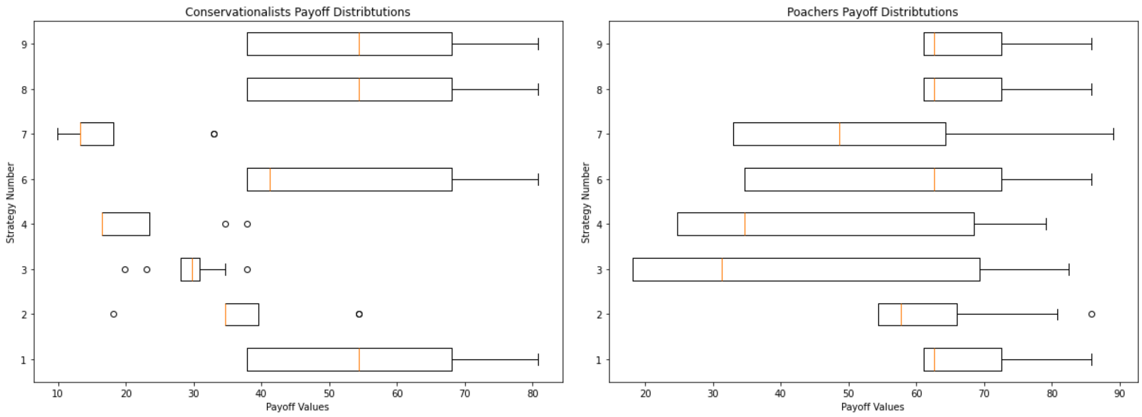
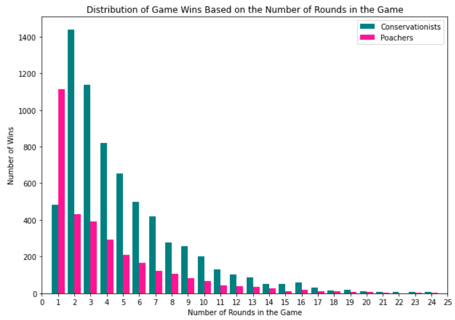
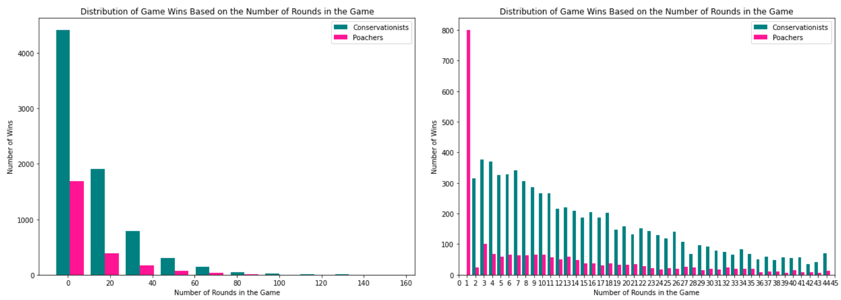


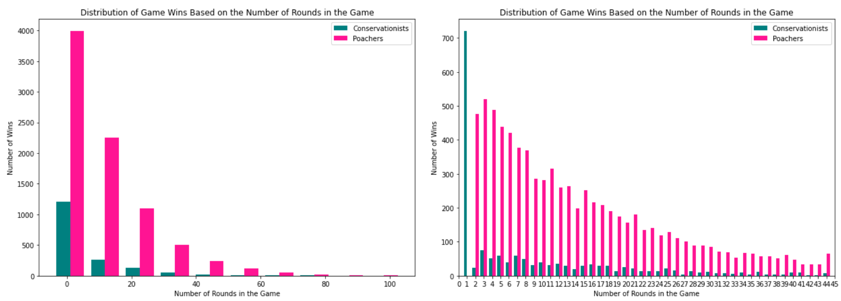
Figure A12. The battlefield payoff vector is [Laws, Marine Reserves, Community]=[0.3333 0.3333 0.3333], meaning that all battlefields contribute equal amounts of the Payoff Bank. Strategy 5 has been omitted due to the inability to pay it with the case of equal battlefields. The budget for conservationists is [High, Low, Low]=[20*(People), 10, 0.1(Population)] and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)]. No strategy will guarantee conservationists will win. However, strategies 1, 6, 8, and 9 have the highest chance of giving conservationists a winning payoff. If poachers play strategies 1, 2, 8, or 9 they will win the most payoff. However, strategy 2 has a lower median payoff that strategies 1, 8, and 9.



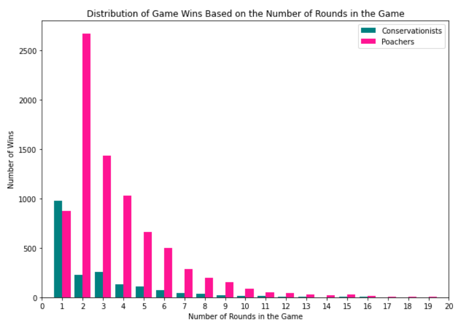
(a) The budget for conservationists is [High, Low, Low]=[20*(People), 10, 0.1(Population)], and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)].



(b) The budget for conservationists is [Low, High, Low]=[1*(People), 200, 0.1(Population)], and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)].

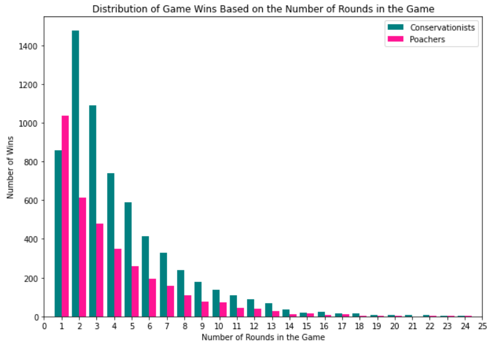


(c) The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)], and the budget for poachers is [Low, High, Low]=[1*(People), 200, 0.1*(Population)].

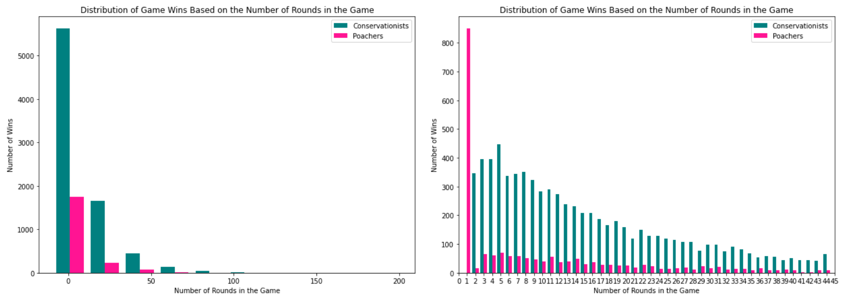


(d) The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)], and the budget for poachers is [High, Low, Low]=[20*(People), 10, 0.1*(Population)].

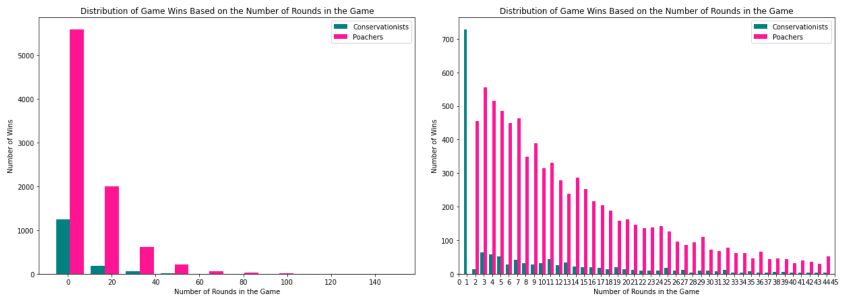
Figure A13. No memory with the battlefield payoff distribution being [Laws, Marine Reserves, Community]=[0.15 0.30 0.55].



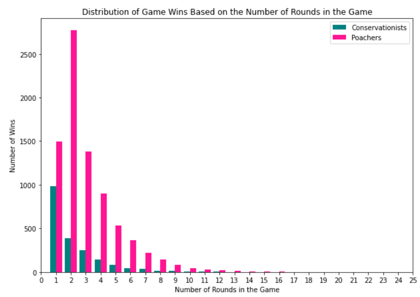
(a) The budget for conservationists is [High, Low, Low]=[20*(People), 10, 0.1(Population)], and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)].



(b) The budget for conservationists is [Low, High, Low]=[1*(People), 200, 0.1(Population)], and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)].

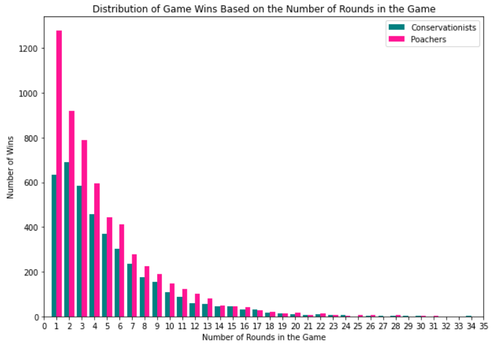


(c) The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)], and the budget for poachers is [Low, High, Low]=[1*(People), 200, 0.1*(Population)].

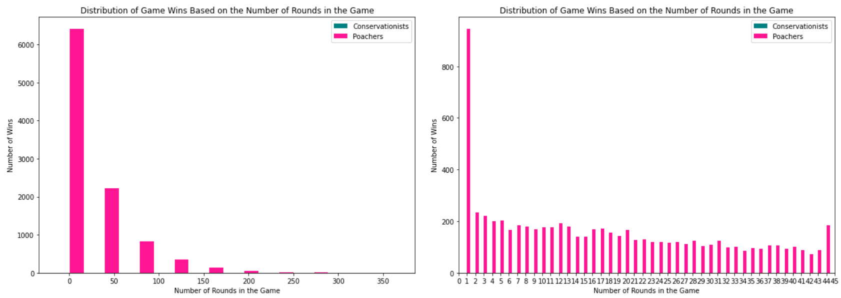


(d) The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)], and the budget for poachers is [High, Low, Low]=[20*(People), 10, 0.1*(Population)].

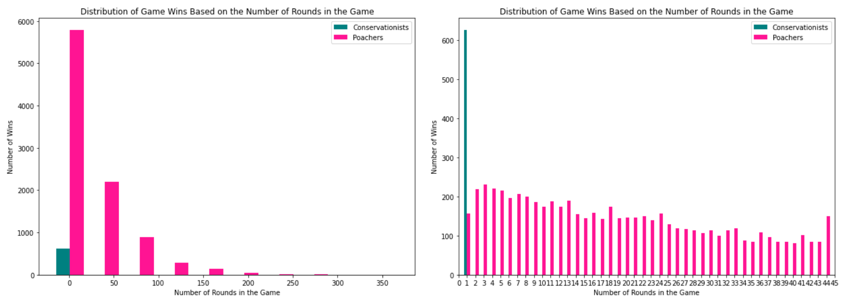
Figure A14. No memory with the battlefield payoff distribution being [Laws, Marine Reserves, Community]=[0.30 0.15 0.55].



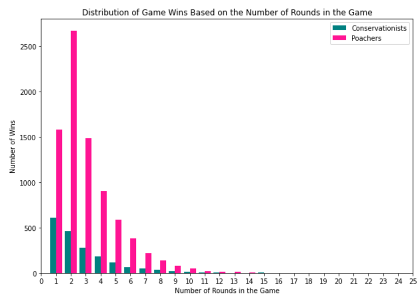
(a) The budget for conservationists is [High, Low, Low]=[20*(People), 10, 0.1(Population)], and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)].



(b) The budget for conservationists is [Low, High, Low]=[1*(People), 200, 0.1(Population)], and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)].

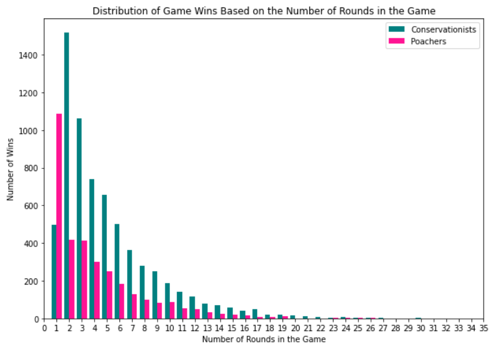


(c) The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)], and the budget for poachers is [Low, High, Low]=[1*(People), 200, 0.1*(Population)].

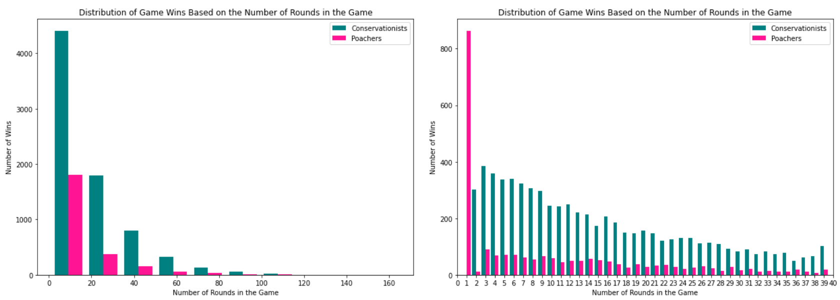


(d) The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)], and the budget for poachers is [High, Low, Low]=[20*(People), 10, 0.1*(Population)].

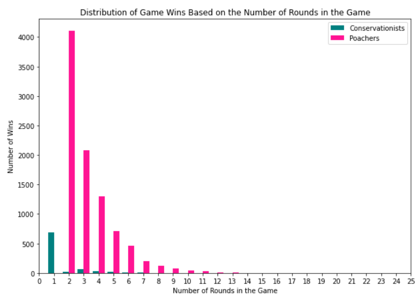
Figure A15. No memory with the battlefield payoff distribution being [Laws, Marine Reserves, Community]=[0.3333 0.3333 0.3333].



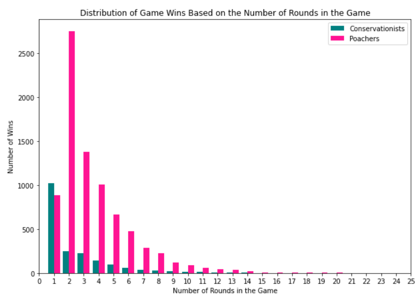
(a) The budget for conservationists is [High, Low, Low]=[20*(People), 10, 0.1(Population)], and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)].



(b) The budget for conservationists is [Low, High, Low]=[1*(People), 200, 0.1(Population)], and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)].

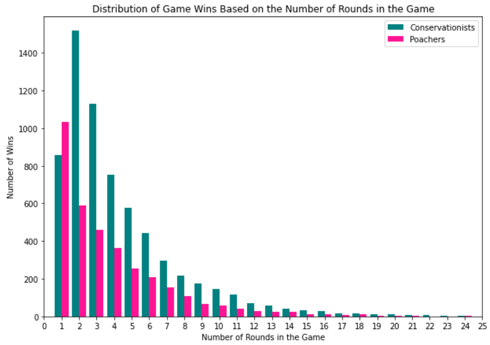


(c) The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)], and the budget for poachers is [Low, High, Low]=[1*(People), 200, 0.1*(Population)].

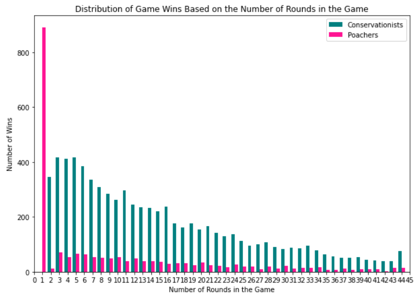


(d) The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)], and the budget for poachers is [High, Low, Low]=[20*(People), 10, 0.1*(Population)].

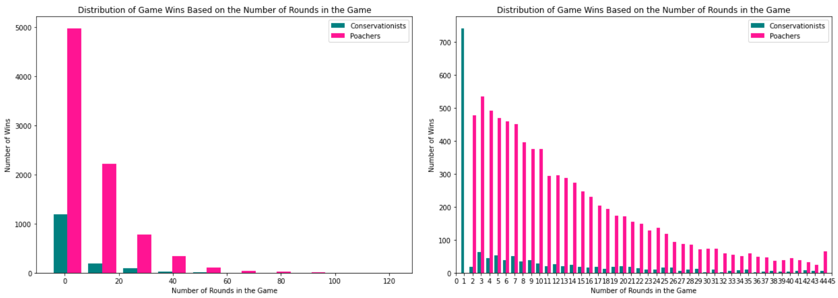
Figure A16. Memory of last round with the battlefield payoff distribution being [Laws, Marine Reserves, Community]=[0.15 0.30 0.55].



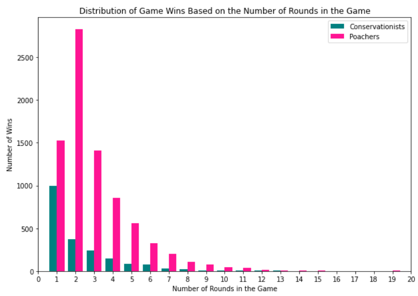
(a) The budget for conservationists is [High, Low, Low]=[20*(People), 10, 0.1(Population)], and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)].



(b) The budget for conservationists is [Low, High, Low]=[1*(People), 200, 0.1(Population)], and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)].

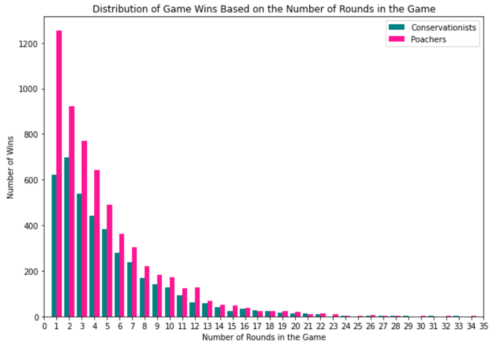


(c) The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)], and the budget for poachers is [Low, High, Low]=[1*(People), 200, 0.1*(Population)].

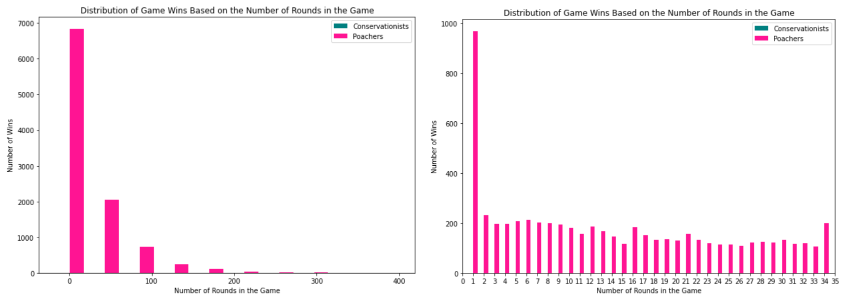


(d) The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)], and the budget for poachers is [High, Low, Low]=[20*(People), 10, 0.1*(Population)].

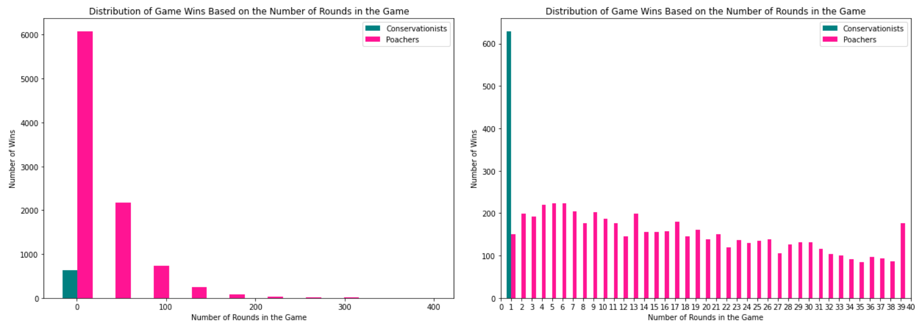
Figure A17. Memory of last round with the battlefield payoff distribution being [Laws, Marine Reserves, Community]=[0.30 0.15 0.55].



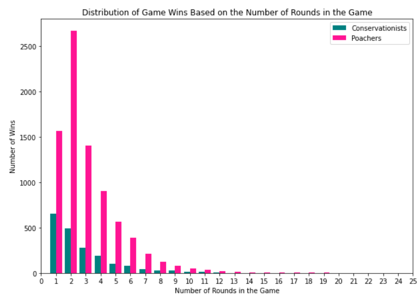
(a) The budget for conservationists is [High, Low, Low]=[20*(People), 10, 0.1(Population)], and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)].



(b) The budget for conservationists is [Low, High, Low]=[1*(People), 200, 0.1(Population)], and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)].

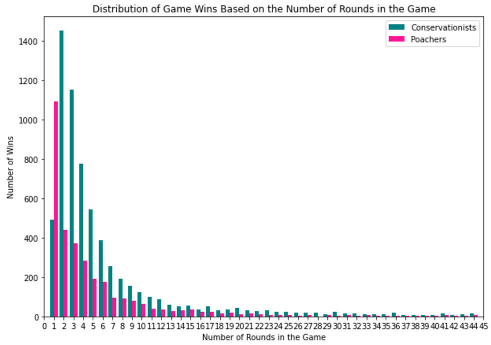


(c) The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)], and the budget for poachers is [Low, High, Low]=[1*(People), 200, 0.1*(Population)].

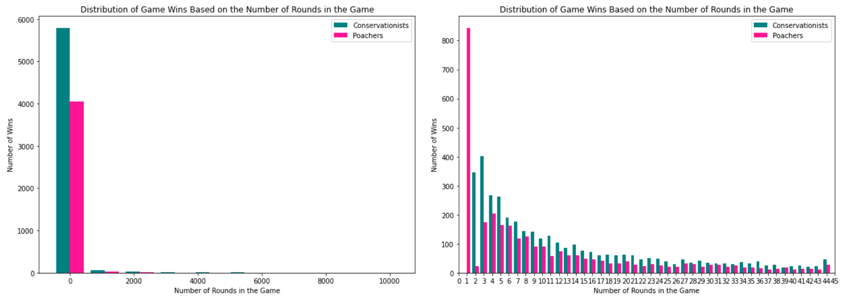


(d) The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)], and the budget for poachers is [High, Low, Low]=[20*(People), 10, 0.1*(Population)].

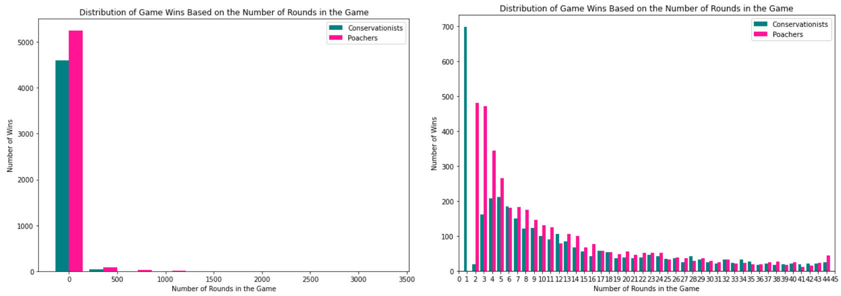
Figure A18. Memory of last round with the battlefield payoff distribution being [Laws, Marine Reserves, Community]=[0.3333 0.3333 0.3333].



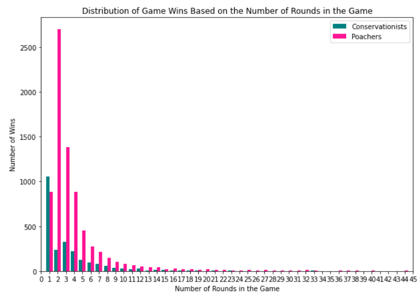
(a) The budget for conservationists is [High, Low, Low]=[20*(People), 10, 0.1(Population)], and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)].



(b) The budget for conservationists is [Low, High, Low]=[1*(People), 200, 0.1(Population)], and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)].

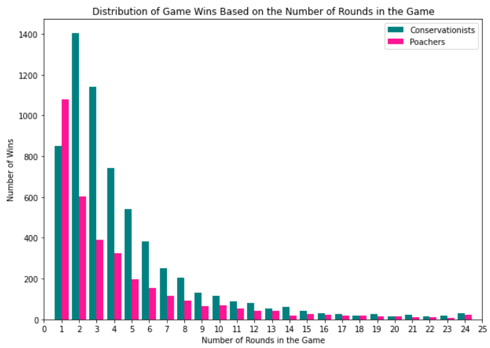


(c) The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)], and the budget for poachers is [Low, High, Low]=[1*(People), 200, 0.1*(Population)].

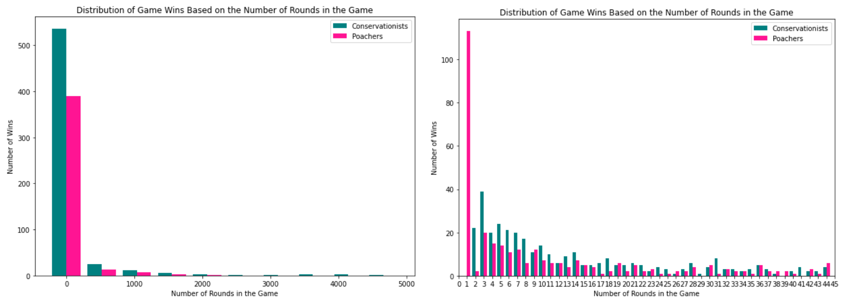


(d) The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)], and the budget for poachers is [High, Low, Low]=[20*(People), 10, 0.1*(Population)].

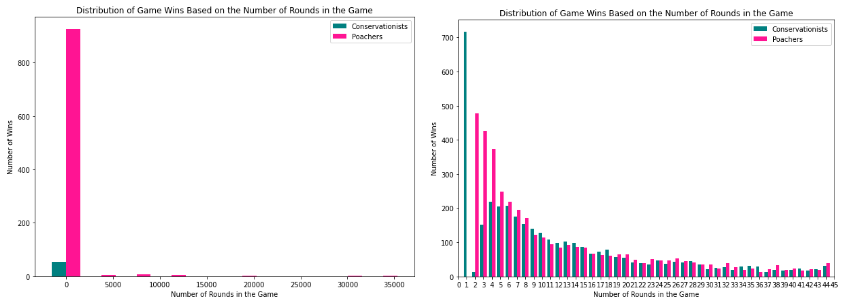
Figure A19. Memory of all previous rounds with the battlefield payoff distribution being [Laws, Marine Reserves, Community]=[0.15 0.30 0.55].



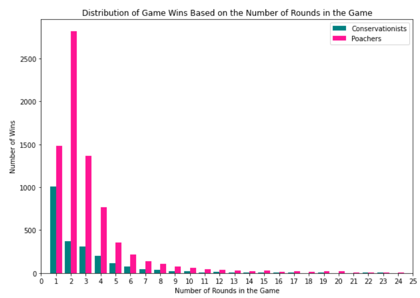
(a) The budget for conservationists is [High, Low, Low]=[20*(People), 10, 0.1(Population)], and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)].



(b) The budget for conservationists is [Low, High, Low]=[1*(People), 200, 0.1(Population)], and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)]. A total of 1000 games were played instead of 10,000 due to run time

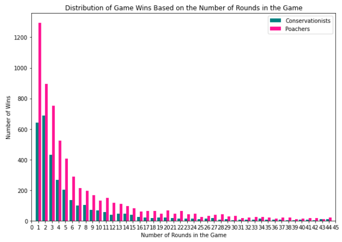


(c) The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)], and the budget for poachers is [Low, High, Low]=[1*(People), 200, 0.1*(Population)]

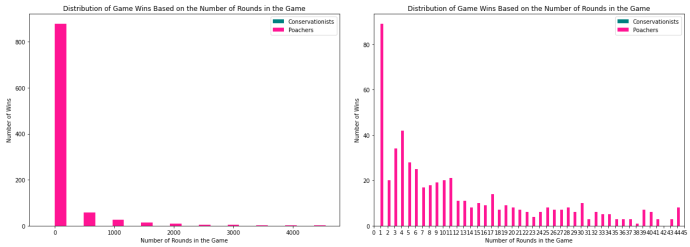


(d) The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)], and the budget for poachers is [High, Low, Low]=[20*(People), 10, 0.1*(Population)].

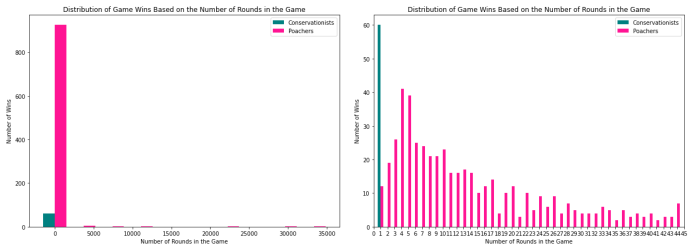
Figure A20. Memory of all previous rounds with the battlefield payoff distribution being [Laws, Marine Reserves, Community]=[0.30 0.15 0.55].



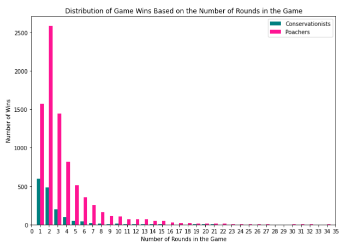
(a) The budget for conservationists is [High, Low, Low]=[20*(People), 10, 0.1(Population)], and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)].



(b) The budget for conservationists is [Low, High, Low]=[1*(People), 200, 0.1(Population)], and the budget for poachers is [Low, Low, High]=[1*(People), 10, 0.9*(Population)]. A total of 1000 games were played instead of 10,000 due to run time



(c) The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)], and the budget for poachers is [Low, High, Low]=[1*(People), 200, 0.1*(Population)].



(d) The budget for conservationists is [Low, Low, High]=[1*(People), 10, 0.9(Population)], and the budget for poachers is [High, Low, Low]=[20*(People), 10, 0.1*(Population)]. 1000 games were played instead of 10,000 due to run time

Figure A21. Memory of all previous rounds with the battlefield payoff distribution being [Laws, Marine Reserves, Community]=[0.3333 0.3333 0.3333].