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EVALUACIÓN DE PRÁCTICAS AGRÍCOLAS SOBRE LA COMUNIDAD DE AVES EN UN PAISAJE CAFETALERO CON DISTINTOS TIPOS DE MANEJO.

Tesis sometida a la consideración de la Comisión del Programa de Estudios de Posgrado en Biología para optar por el grado de Maestría Académica en Biología

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Dedicatoria

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Resumen

Entre los varios métodos de producción agrícola extensiva existentes, se producen distintos impactos ambientales y sociales. Uno de los más grandes constituye la pérdida de hábitat para la vida silvestre. La agricultura sostenible pretende balancear la producción con el bienestar social y ambiental, sin embargo, uno de los retos más grandes es la conservación de la vida silvestre. Estas poblaciones no están restringidas a los parques nacionales o tierras protegidas, sino que se movilizan a través de un paisaje variado. Aumentar el conocimiento ecológico de las poblaciones de aves tropicales que utilizan paisajes productivos nos permitirá informar cuál es el efecto del manejo de la agricultura en la conservación de especies.

Aquí, nuestro objetivo es evaluar el efecto de las prácticas agrícolas implementadas como parte de un programa de sostenibilidad en las fincas cafetaleras, sobre la comunidad de aves. Específicamente: Identificar umbrales donde cambia la probabilidad de ocupación de especies de aves, en relación con la complejidad estructural vegetal del paisaje. Estimar cambios en las frecuencias de uso del hábitat de las aves debido prácticas agrícolas en las plantaciones de café, y por último analizar las relaciones entre la percepción de bienestar de los productores y la comunidad de aves en las fincas.

Los atributos de complejidad de la vegetación que exploramos en este estudio, biomasa sobre el suelo y altura del dosel, están relacionados con las prácticas de manejo dentro de las fincas cafetaleras. Para calcular la probabilidad de ocupación utilizamos puntos de conteo distribuidos en un paisaje cafetalero. Encontramos que la relación entre la ocupación de aves y las características de la vegetación es específica de la especie. La altura del dosel fue el atributo que predijo mejor la probabilidad de ocupación para las especies dependientes del bosque. La biomasa demostró predecir el aumento de las probabilidades de ocupación de muchas especies comunes. Con base en esto, enumeramos tres recomendaciones para mejorar la complejidad de la vegetación en las fincas cafetaleras y, en consecuencia, aumentar la ocupación de este paisaje por parte de las aves.

Utilizamos grabadoras pasivas para detectar seis especies de aves que utilizan activamente las parcelas de café para forrajeo, anidación y refugio y estimamos los cambios en la

detección de aves en respuesta a la poda y las aplicaciones de agroquímicos en las plantaciones de café. Las aves que se alimentan en el suelo, como el gorrión orejiblanco (*Melozone leucotis*), se vieron afectadas por la poda de los cafetos de forma más evidente que otras especies. Las aplicaciones de agroquímicos afectan la detección de aves en general, pero varía entre especies. Las diferencias entre especies en las respuestas se explican por sus hábitos de alimentación y comportamiento. Identificar la forma en que las aves reaccionan ante estas prácticas nos permitió sugerir seis acciones para disminuir los efectos negativos de la aplicación de químicos y la poda de los cafetos.

Finalmente, exploramos si las percepciones de bienestar ambiental de los agricultores que producen café, medidas a través de un índice de progreso social, están relacionadas con la composición de la comunidad de aves de las fincas cafetaleras calculados previamente. Descubrimos que las preguntas utilizadas en la encuesta que compone el índice no reflejan ni siquiera indirectamente la percepción que tienen los caficultores sobre la comunidad de aves. La leve relación observada podría derivar indirectamente de componentes sobre la percepción de bienestar relacionados con la calidad del agua. Los índices que utilizan encuestas y tienen como objetivo comprender las percepciones de bienestar y sostenibilidad deberían incluir preguntas sobre las percepciones de las personas sobre la diversidad biológica que las rodea.

Índice de cuadros

Capítulo 1.

Capítulo 2.

Índice de figuras

Capítulo 1.

Capítulo 2.

Capítulo 3.

INTRODUCCIÓN

Uno de los retos más grandes para la conservación en paisajes agrícolas es el involucramiento del sector productivo (productores y empleados) de forma activa en las prácticas de conservación (Philpott, & Dietsch, 2003; Foley et al., 2011). La agricultura es necesaria para satisfacer la demanda mundial de alimentos. Sin embargo, esta ha producido un aumento en la homogenización del paisaje debido a la transformación de la cobertura natural en áreas agrícolas y la consiguiente pérdida de diversidad (Ruiz-Gutiérrez et al., 2010; Foley et al., 2011). La transformación y eliminación de ambientes naturales es particularmente relevante en zonas tropicales, donde muchas especies se ven afectadas por la pérdida del hábitat natural causado por la agricultura extensiva y monocultivista (Fayle et al., 2010; Carlson et al., 2918; Dhandapani et al., 2019).

Existen varios métodos de producción agrícola y cada uno provoca distintos impactos ambientales y sociales (Laurance et al., 2014). Los monocultivos de soja, piña, caña de azucar y palma aceitera cubren grandes áreas que aumentan la erosión del suelo, la contaminación de las aguas por agroquímicos, y la pérdida de hábitats naturales (Fayle et al., 2010; Obando, 2017; Carlson et al., 2018; Dhandapani, et al., 2019). Por otra parte, cultivos mixtos y rotativos como las hortalizas y frutas tienen un menor impacto en la pérdida de hábitats, pero producen un sobre agotamiento del suelo por la cantidad de químicos aplicados (Martin-Gorriz et al., 2020). La agroforestería es una práctica en la que se combina la producción agrícola con la presencia de árboles o remanentes de bosque y puede aumentar los rendimientos de producción agrícola y los nutrientes del suelo, reducir la erosión, y retener el agua (Waldron et al., 2017).

Un ejemplo de cultivo que se maneja como agroforestería es el café cultivado bajo sombra (Haggar et al., 2001), en el que se usan árboles frutales y maderables para crear un ambiente de sombra a la planta y que resulta en un paisaje agrícola más heterogéneo (Romero-Alvarado et al., 2002; Philpott et al., 2008; Hernandez et al., 2013; Chang et al., 2018; Estrada-Carmona et al., 2019; Narango et al., 2019; Sandoval, 2019). Dentro de esta modalidad, una práctica aún más sostenible, es manejarlo de manera orgánica. Esta práctica se basa en la gestión de la finca y los derivados de su producción para generar los nutrientes para el mismo cultivo, en lugar de utilizar insumos externos y artificiales como los fertilizantes químicos (Lotter, 2003). Además, emplea productos degradables y el control biológico para contrarrestar las plagas (Lotter, 2003; Vandermeer et al., 2010), generando un menor impacto en el suelo y en la biodiversidad (Haggar et al., 2001). Por el contrario, el café expuesto al sol tiene una mayor producción por hectárea, pero mantiene una menor diversidad asociada y requiere más insumos químicos como el nitrógeno, para complementar el desbalance de nutrientes del suelo debido a la producción (Haggar et al., 2011).

En Costa Rica, se cultiva café (*Cooffea arabica*) bajo sombra, por que brinda una mejor calidad de taza (Toledo & Moguel, 2012; Vignola et al., 2018; Estrada-Carmona et al., 2019). Cada especie de café necesita distintos requerimientos de sombra o de agroquímicos. Por ejemplo, C. arabica que es la especie más común en Costa Rica, es menos resistente a las plagas, lo que implica un mayor uso de químicos para aumentar su producción (Van der Vossen et al., 2015). En la India por otro lado, los productores de *C. canephora* utilizaron menos pesticidas lo cual puede influir en la mayor abundancia de insectos presentes en los cultivos que suponen alimento para las aves insectívoras (Chang et al., 2018). Encontrar la mejor manera de mantener la producción de café y las ganancias justas de los productores sin comprometer la calidad del ambiente es un reto de sostenibilidad (Kilian et al., 2006; Valkila, 2009).

La sostenibilidad se define como el equilibrio de los aspectos sociales, ambientales y económicos para el desarrollo de las actividades humanas (Munier, 2005). Implica cambios en el comportamiento, los patrones de producción y consumo, y la percepción social del ambiente (Munier, 2005). La agricultura sostenible pretende satisfacer la demanda de alimentos de la población, de una manera socialmente justa, conservando los servicios ecosistémicos y maximizando el beneficio para la sociedad (Tilman et al., 2002). Existen distintas prácticas de sostenibilidad que promueven el aumento de la cobertura arbórea, la protección del suelo y del agua así como las condiciones sociales y éticas en las fincas de café a través de programas, y certificaciones internacionales como Organic, Fair Trade, Rainforest Alliance, Utz Kapeh, y Shade Bird Friendly (Raynolds et al., 2007). Estas certificaciones funcionan por medio de incentivos de acceso a mercados, de ganancias, u otros (Raynolds et al., 2007). Sin embargo, si los programas no son evaluados periódicamente para verificar que las prácticas produzcan una mejoría y eventual equilibrio en la cobertura vegetal, la calidad de los suelos, el agua y en la biodiversidad no se puede asegurar que cumplen con objetivos de sostenibilidad que se promueven (Milder et al., 2015).

Efecto de la complejidad vegetal dentro de sistemas productivos sobre la biodiversidad

Al conjunto estructural que cubre una superficie terrestre producto de la organización espacial de la vegetación, se le conoce como cobertura vegetal (Morales, 2000; Nieto & Nieto, 2016). La cobertura puede ser medida mediante imágenes satelitales calculando el área cubierta por cada tipo de vegetación (Lazalde et al., 2006), o en el campo evaluando la composición florística y midiendo el área cubierta en las parcelas de interés (Rodríguez-Navas & Hilje-Quirós, 1986). La cobertura vegetal de los suelos puede ser natural como pastos y pastizales arbolados, sabanas, sitios con distinto grado de vegetación y bosques maduros, o puede estar desprovistos de su vegetación original pero cubiertos con cultivos u otra vegetación debido a las acciones humanas (Morales, 2000; Nieto & Nieto, 2016).

En paisajes agrícolas la cobertura puede cambiar drásticamente en periodos cortos de tiempo debido al cambio de cultivos y uso de los suelos (Muschler, 2001). El café o los árboles frutales son tipos de cobertura perennes lo cual quiere decir que no se desnuda el suelo con cada cosecha, mientras que los cultivos estacionales o anuales como la piña o la caña se cosechan dejando la tierra descubierta provocando mayor erosión y un cambio abrupto en la cobertura (Muschler, 2001). Los diferentes tipos y niveles de cobertura en los cultivos pueden tener efecto sobre la diversidad de fauna presente. En un estudio en sistemas agrícolas de palma aceitera en Malasia se descubrió que la poda selectiva del dosel de la plantación, estaba asociada a un mayor número de gremios de forrajeo de aves porque permite la entrada de luz para el desarrollo y el aumento de la cobertura del sotobosque (Azhar et al., 2013).

La cobertura vegetal varía también en su complejidad estructural, esta usualmente se define como una serie de medidas que se hacen de la posición, distribución y tamaño de los elementos de vegetación (Zellweger et al., 2013). Estos elementos se denominan atributos y son, por ejemplo, la altura, número de tallos, número de troncos caídos, cobertura del dosel, densidad y distribución de los árboles, entre otros (McElhinny et al., 2005). Otra variable relacionada a la caracterización vegetal de un área es también la biomasa sobre el suelo, que se define como toda la biomasa vegetal viva sobre el suelo, incluido el tallo, el tocón, las ramas, la corteza, las semillas y el follaje (Ravindranath & Oswald, 2008).

En bosques de filipinas rodeados de un paisaje agrícola, se encontró que la riqueza de especies de aves endémicas y de especies en peligro de extinción estaba relacionadas positivamente con la variación en la biomasa sobre el suelo (Singh et al., 2017) al igual que en Brasil donde la variación de la riqueza de aves, era explicada en un 70% por la variación de la biomasa sobre el suelo (Lees et al., 2015). En una zona cafetalera de Colombia se determinó que el café con sombra puede ser un hábitat adecuado para el paso de aves migratorias (Céspedes & Bayly, 2019). Sin embargo, siguen siendo necesarios bosques y sitios con una biomasa vegetal más alta para la permanencia de especies de interés para la conservación de algunas especies como la Reinita Canadiense *Cardelina canadensis* (Parulidae) (Céspedes & Bayly, 2019).

En Costa Rica las fincas cafetaleras suelen utilizar árboles para proporcionar sombra sobre el cultivo, estos árboles proporcionan alimento y refugio a las aves y otros animales como mamíferos o reptiles (Narango et al, 2019, Hernández et al, 2013). Utilizan también cercas vivas, como división entre parcelas, que cuando tienen estratos variados promueven el uso y paso de las aves por espacios agrícolas y productivos (Estrada-Carmona et al, 2019). A su vez, las aves transportan semillas desde los remanentes de bosque hacia los espacios agrícolas de los que hacen uso, favoreciendo la dispersión de plantas desde el bosque hacia zonas productivas (Barrantes & Pereira, 2002). Usualmente las fincas son bordeadas o atravesadas por ríos y estos hábitats juegan un papel fundamental para mantener las comunidades de animales en paisajes agrícolas (Domínguez-López & Ortega-Álvarez, 2014). Esas prácticas en el cultivo cafetalero resultan en una mayor variación en la complejidad estructural vegetal en los cultivos y sus alrededores, la cual está también relacionadas con una mayor diversidad de aves (Gordon et al., 2007; Leakey, 2014; Singh et al, 2017).

Por estas razones la complejidad estructural es una característica que se puede usar para evaluar en conjunto esas prácticas agrícolas y su relación con la ocupación de especies de aves prioritarias para la conservación (aves que se encuentren en las lista roja de especies amenazadas de la UICN como *Procnias tricarunculatus* (IUCN, 2020), en la lista nacional de especies en peligro y con poblaciones reducidas y amenazadas como *Melozone leucotis* y *Chlorophonia callophrys* (SINAC, 2017), y aves migratorias cuyas poblaciones hayan declinado drásticamente como *Cardelina canadensis* (Céspedez & Bayly, 2019)."

Efecto de las prácticas agrícolas en la riqueza de especies

El principal objetivo de los medios de producción agrícola a nivel general, es aumentar la producción manteniendo los costos razonables y minimizando el gasto de recursos (Nicol & Nicol, 2018). Para esto se utilizanlos sistemas de riego, el mejoramiento de variedades vegetales, la fertilización y mejora de suelos, el cultivo hidropónico, entre otros (Puignau, 1995). La eficiencia obtenida en el proceso de producción tiene consecuencias para el ambiente, la salud humana y la biodiversidad como ha sido observado en otros cultivos (Gamboa, 2005; Lajmanovich et al., 2012, Segura, 2015). En el cultivo de café, por ejemplo, los químicos como el insecticida clorpirifos utilizado para combatir la broca del café *Hypothenemus hampei* y otras plagas, pueden ser lavados hacia las aguas superficiales y mantos acuíferos cuando caen las lluvias, ocasionando también la contaminación de otros ecosistemas (Soares et al., 2017). Este tipo de agroquímicos tienen el potencial de bioacumularse en el ganado de producción de leche (Vallecilla et al., 2010), provocar consecuencias en el desarrollo neurológico de seres humanos (Wesseling et al., 2006) e impedir la capacidad de orientación en aves migratorias (Eng et al., 2017). Finalmente, el uso de ese tipo de insecticidas no solo elimina la broca, sino que a muchos insectos que son fuente alimenticia de animales (Chang et al., 2018).

Los impactos correspondientes a la poda y cosecha dependen del tipo de cultivo. Por ejemplo, en cultivos como la caña y la piña que requieren la remoción completa de la capa vegetal que cubre el suelo, lo que impiden que los sitios de cultivo sean utilizados por los animales para desplazarse o forrajear provocando el aislamiento reproductivo de algunas especies (Ripperger et al., 2015; Becca et al., 2017). Sin embargo, en cultivos donde no se poda completamente la cobertura vegetal como los cítricos y el café, se permite que algunas especies de fauna tengan una capa vegetal lo suficientemente compleja, sobre la cual pueden desplazarse y vivir (Santos & Tellería, 2006; Estrada-Carmona et al, 2019).

Comprender el uso que hacen los animales de los campos agrícolas dependiendo de la época del año y de las prácticas aplicadas permite tomar decisiones de manejo en paisajes productivos. Por ejemplo, en el caso de plantaciones forestales en Canadá, la práctica de mantener agregaciones de árboles en la zona de cosecha, aumenta la abundancia media de mamíferos pequeños respecto a la práctica de mantener árboles dispersos (Sullivan & Sullican, 2018). En campos de arroz en California se reportó que extender las inundaciones post-cosecha tres semanas, incrementaba de manera importante la disponibilidad del hábitat para distintas aves migratorias (Sesser et al., 2018).

Para la producción del café se realizan prácticas en épocas definidas del año (Vieira, 2008), que pueden afectar la biodiversidad. La aplicación de agroquímicos como insecticidas, nematicidas, fungicidas y fertilizantes se da de junio a setiembre, algunos se aplican de forma foliar por medio de atomización líquida y otros como el nitrógeno se colocan bajo cada planta de café para que sean absorbidos por el suelo en los primeros meses de la época lluviosa (Barquero, 2013) lo que coincide con la época reproductiva de muchas aves residentes (Skutch, 1950). Además, los agroquímicos más frecuentemente utilizados por los productores de café son los nematicidas como el Counter, los fungicidas a base de cobre para combatir la roya, como el Cuprox que se aplican durante todo el año (Barquero, 2013).

La cosecha del café, que es de manera manual y necesita de muchas personas, se da entre los meses de diciembre a febrero (Haight, 2007), y coincide con la época migratoria de aves que vienen de Norteamérica al final del verano y principio del otoño (Marra et al., 2006; Faaborg et al., 2010). Posterior a la cosecha, en los meses de marzo y abril se practica la poda, que coincide con la época de retorno de las aves migratorias, febrero-marzo y el inicio de la época reproductiva de la mayoría de las aves residentes, abril-junio (Skutch, 1950). Debido a esto, se espera que la aplicación de agroquímicos, la poda y la cosecha tengan un efecto en la probabilidad de ocupación de las aves en los cafetales, después de la aplicación de cada una de las prácticas agrícolas mencionadas.

Percepciones del medio ambiente y la biodiversidad

Existe una presión por parte del consumidor y de los tomadores de decisiones para que el agricultor proteja o mejore el hábitat en sus fincas de manera que la producción sea compatible con la conservación de la vida silvestre (Kross et al. 2018). Sin embargo existe una falta de conocimiento, por parte de los tomadores de decisiones, sobre la percepción que tienen los productores acerca de la calidad del ambiente y de la fauna silvestre en sus fincas (Kross et al. 2018). Así como un desconocimiento del bienestar social de los propios agricultores y trabajadores asociados a la producción de alimentos (Haight, 2007). Para que la producción agrícola sea considerada sostenible debe también asegurar el desarrollo y bienestar social de los productores y trabajadores (Kilian et al., 2006).

Medir y determinar el nivel de desarrollo y bienestar humano es una tarea compleja. No puede calcularse únicamente mediante el ingreso *per capita* en una familia, ni por el producto interno bruto de un país o región (Rosenberg, 1994; Mancero, 2001). Para obtener buenas aproximaciones se calculan diversos índices. El Indice de Desarrollo Humano (IDH) comenzó a usarse en 1990 y ha pasado a constituir uno de los principales instrumentos de comparación entre países, constituye una guía, no un valor exacto (Rosenberg, 1994). El índice de progreso social (IPS) es una aproximación integral sobre la salud de una sociedad. Funciona de manera independiente pero complementaria a los índices económicos (Porter, et al., 2014). El IPS está compuesto por tres secciones donde se evalúan: (1) las necesidades básicas, (2) las bases para el bienestar, y (3) las oportunidades. Cada una con subsecciones y calificaciones asociadas a las respuestas y percepciones que reflejan los ciudadanos en las encuestas (Porter et al., 2014).

Cada una de las secciones del IPS está compuesta por cuatro componentes. En la sección de bases para el bienestar, se encuentra el componente de calidad ambiental. La calidad del ambiente es valorada de manera cualitativa. Las respuestas que dan las personas al contestar las encuestas para la construcción del IPS, están influenciadas por la percepción que tengan sobre distintas características que observan en el ambiente. Por ejemplo, la claridad del agua de los ríos en sus comunidades, el manejo de los desechos sólidos, la cantidad de áreas verdes que se encuentran cerca de sus hogares (Cottet et al., 2013). Incluso la abundancia y diversidad de aves que observan en sus jardines (Hedblom & Gunnarsson, 2017). Un estudio sobre las percepciones respecto a aves y murciélagos en California, mostró que los agricultores asociados con la producción de frutas tienen una percepción menos positiva sobre las aves y murciélagos. Mientras que los agricultores que producen cultivos no consumidos por estos animales los perciben como aliados para el control de otras pestes.

Estas percepciones positivas o negativas que representan distintos gremios de aves para los agricultores, pueden influir en la percepción de bienestar o en la percepción de la calidad del ambiente que reportan. Finalmente, la percepción de calidad del ambiente es una variable más, utilizada para valorar el bienestar personal o familiar, así como lo es el nivel de ingresos o el acceso a la salud (Porter et al., 2014). Esto no implica que al haber mayor diversidad de aves las personas vayan a percibir una mejor calidad ambiental automáticamente. Sin embargo, explorar si la presencia de ciertas aves o gremios de aves tiene relación con las percepciones de calidad ambiental de los productores de café puede contribuir a la construcción de indicadores de bienestar para los programas de sostenibilidad. Además de contribuir a comprender la aceptación que puedan tener los productores ante propuestas de manejo sostenible (Alessa et al., 2003; de Snoo et al., 2013).

Capítulo 1. Bird species occupancy in relation to the structural vegetation complexity of a coffee landscape.

Abstract

Wildlife populations are not restraint to national parks or protected land. Increasing the ecological knowledge of tropical bird populations that use productive landscapes will allow us to inform what is the effect of management and restoration of agriculture on species conservation. Here, we aim to identify thresholds where the probability of occupation of birds increases in relation to the vegetal structural complexity of the coffee landscape. The vegetation attributes we explore in this study are related to management practices within the coffee farms. Shade-trees and life fences contribute to increasing the average Canopy Height of a plot. Above Ground Biomass is related to the occurrence of shade-trees and coffee plants. The relation between bird occupancy and vegetation characteristics was found to be species-specific. Canopy Height was the attribute that better predicted occupancy probability for forest dependent species. Above Ground Biomass proved to predict increasing occupancy probabilities for many common species. Based on this, we list three recommendations to improve vegetation complexity on the coffee farms and as consequence, increase bird occupancy of this landscape.

Key words: Sustainability, Agriculture impacts, conservation, productive landscapes.

The direct participation of the agricultural sector (i.e., owners, producers, workers) in the sustainability of agricultural landscapes, is still a challenge (Philpott, & Dietsch, 2003; Foley et al., 2011). The transformation and elimination of natural habitats are particularly relevant in tropical areas, where extensive monoculture affects many species through the loss and fragmentation of natural habitats (Fayle et al., 2010; Carlson et al., 2918; Dhandapani et al., 2019). However, efforts to improve sustainable production increased during the last decade, motivated by agriculture companies and farmers (El Chami et al., 2020), in response to consumer's demand. To know if those efforts will impact positively the conservation of natural habitats, it is necessary to develop indicators that will help us to evaluate the species-habitat relationships in response to agricultural management. Therefore, increasing the ecological knowledge of tropical wildlife populations using productive landscapes will allow us to inform what is the effect of management and restoration of productive landscapes on species conservation (Ortega-Álvarez et al., 2018).

In Latin America, there are several opportunities for habitat restoration and the protection of natural habitats within agricultural landscapes (Coppus, et al., 2019). Among these opportunities, there are strategies of agroforestry and regenerative agriculture, which aim to increase vegetation complexity together with productivity targets (Andrade et al., 2020) To evaluate the effects of the management strategies in agricultural practices in wildlife conservation, it is necessary to use indicators based on quantitative data (Tscharntke, et al., 2015). Birds are one of the most common indicators of habitat quality, because, they are easier to detect and identify than other animal groups (Faixedas, et al. 2020), have practical and effective field monitoring methods (Ruiz-Gutierrez et al., 2020), are diverse and widely spread (Jetz et al., 2012), and they are sensitive to changes in the environment since they occupy different habitats and food guilds (Järvinen & Väisänen, 1979; Koskimies, 1989; Gregory et al., 2005).

Coffee producers have the potential of becoming allies for biodiversity conservation; they often use trees to provide shade over the crop and these trees provide food and shelter for birds and other animals (Narango et al., 2019, Hernández et al., 2013). Living fences are used as a division between plots that promote the use and movement of birds through agricultural and productive areas (Estrada-Carmona et al., 2019). Birds disperse seeds from forest remnants to agricultural spaces used by them (Barrantes & Pereira, 2002; Variar et al., 2021). Farms are usually bordered or crossed by rivers with protected zones in the margins. These riparian habitats maintain animal communities in agricultural landscapes because are the source of many species that occur in agricultural areas (Domínguez-López & Ortega-Álvarez, 2014). All these practices are often considered part of sustainable strategies for coffee production (Hernández et al, 2013; ECOM, 2019; Estrada-Carmona et al, 2019) and can be evaluated by studying the response of the bird community to the environmental variation (Järvinen & Väisänen, 1979; Koskimies, 1989; Gregory et al., 2005, Estrada-Carmona et al., 2019).

There are several programs and certifications of sustainable production in coffee farms, like, AAA Sustainability program, Rain Forest alliance certification, Bird friendly certification, C.A.F.E practices program, (ECOM, 2019; Rain Forest Alliance, 2022; Smithsonian´s National Zoo & Conservation Biology Institute 2022; Starbucks, 2022). These certifications aim to achieve sustainability standards that might be periodically evaluated to verify that they produce an improvement in vegetation cover, quality of the soil, water, and biodiversity, otherwise it cannot be assured that they meet the sustainability objectives that were intended (Milder et al., 2015). Here, we show an effective and scalable way to evaluate, but also to inform, agricultural management decisions using the AAA program as our model. We use birds as indicators and vegetation complexity of the landscape as a proxy to evaluate management practices of the AAA program, such as forest conservation, shade trees within plots, and preservation of riparian habitats. Therefore, our main objective is to identify thresholds where the probability of occupation of birds increases in relation to the vegetal structural complexity of the coffee landscape. Those thresholds then can be used to define goals for the sustainability objectives, initiating a cycle of ongoing adaptation.

Methods

Study site

This study was conducted in the San Ramón region of Alajuela (10° 13’ N, 84° 35’ W), between 1,000 and 1,300 m a.s.l. and the basins of the Grande de San Ramón River and the Barranca River. Coffee farms are located throughout the region in the districts of Santiago, San Rafael, Alfaro, Piedades Norte, Piedades Sur, and Concepción. The land cover is a mix of crops (coffee, tomato, sugar cane, ornamental plants and smaller-scale subsistence crops of beans, corn, and oranges), grasslands, farms, and forest remnants. In addition, there are cattle pastures, poultry and pig farms. Wooded areas are remnants of riparian forests, protection zones for springs and creeks or farm plots that were abandoned and have regenerated naturally. The coffee farms that we studied have areas ranging from 1 to 12.6 ha. The farms are family owned and managed by several family members. All farms grown the *Coffea arabica* species, although they alternate in varieties such as Caturra and Catuaí.

Bird survey

To have a gradient of different types of cover and management throughout the coffee landscape, we carry out 160 point counts. We located 80 points in coffee farms that are within the AAA Sustainable Quality™ program of ECOM Agroindustrial (ECOM, 2019), 40 points within coffee farms without sustainability certification, 20 points in wooded areas, and 20 points located in open areas such as abandoned pastures, cane fields, and pastures.

In each of the 160 points, we carried out counts following the protocol of two-band count points, established in the PROALAS manual (Ruiz et al., 2020). Each point was separated from each other by at least 200 m, to avoid counting the same individuals in two places within the same count. Points were more than 150 m away from any road to avoid interference from traffic noise and the effect of roadside habitats that do not represent the habitats of interest. Each counting point consists of two bands. The first one with a radius of 30 m around each previously established fixed point, in which all birds seen and heard within the perimeter were counted. The second band consists of the area outside that 30 m where birds seen and heard were counted.

We carried out the counts, from January to February and from July to August on 2020 and 2021 to include the dry season (the period in which the wintering migratory birds that use the coffee plantations are found) and the rainy season (the period after the reproductive peak and where there is a greater number of resident birds in the coffee plantations). Surveys were done from 6:00 to 10:00 h for 10 minutes each. We conducted four replicates in each sampling season for each of the 160 count points. We visited 12 counting points per day making a replica per person (2 persons/day), and completing four replicas per point every two days.

Plant structural complexity of the farms

To estimate the structural complexity of the landscape we used information extracted from laser detection and ranging (LIDAR) images obtained from the Global Ecosystem Dynamics Investigation (GEDI). GEDI is a space mission for lidar imaging specifically designed for the study of forest structure (Dubayah, et al., 2020). These images provide information such as canopy height with a resolution diameter of 25 m and an accuracy of 2.3 cm (Duncanson, et al., 2020). We used above ground woody live biomass data (Baccini, 2012) at a 30 m resolution.

Data analysis

We applied single-season occupancy models (MacKenzie et al., 2017) to the detection histories of birds for the rainy season and the dry season of 2020 and 2021. We used four vegetation complexity characteristics of the habitat, as model covariates for occupancy and detection: Canopy height at 30m (CH30), Canopy height at 100m (CH100), Above Ground Biomass at 30m (AGB30), and Above Ground Biomass at 100m (AGB100), for each season. We modeled occupancy (ψ) and detection (p) probabilities as a function of these four covariates using "unmarked" package in R statistical software (Fiske and Chandler, 2011).

We constructed our candidate model set by modeling occupancy probability as a function of CH30, CH100, AGB30, and AGB100, using the "dredge" function in the "MuMIn" package (Barton, 2016). Model selection and model averaging of regression coefficients were performed based on the second-order Akaike's information criterion (AICc) and the associated weight of the model (ωi) (MacKenzie et al., 2017), selecting the model based on an information-theoretic approach (Burnham and Anderson, 2002), using the "MuMIn" package (Barton, 2016; Burnham and Anderson, 2002). We modeled occupancy probability relationships with the habitat characteristics to identify thresholds for management practices. We used model-averaged estimates of model coefficients to generate predictive curves of occupancy according to the given habitat characteristics.

Results

Species selection

We detected 210 species total between 2020-2021 (see appendix A), most detected species were: *Cantorchilus modestus* (Cabanis´s Wren), *Basileuterus delatrii* (Chestnut-capped Warbler), *Psilorhinus morio* (Brown Jay), and *Amazilia tzacatl* (Rufous-tailed Hummingbird). Some of the detected species which are of conservation concern due to their reduced range and endemism were: *Procnias tricarunculatus* (Three-wattled Bellbird), *Michrochera cupreiceps* (Coppery-headed Emerald), *Melozone cabanisi* (Cabanis's Ground-Sparrow) (SINAC, 2017; IUCN, 2022). We selected species that had over 100 observations, for the occupancy models to be conclusive. In addition, we left out species that had over 500 observations since their occupancy probabilities were uninformative to determine the effect of vegetation attributes (38spp., see appendix A). From the aforementioned 38 species, we obtained fitted models of occupancy probabilities for over 20 species for each year per season (see figures 1 and 2).

Effects of Vegetation attributes on species occupancy probabilities

Our average values (M) and standard deviation (SD) of vegetation attributes for coffee point counts where: CH30 (M= 11.45, SD=2.8), CH100 (M=11.10, SD=2.6), AGB30 (M=64.65, SD=21.1), and AGB100 (M=671.2, SD=177.9). We found that the relation between bird occupancy and vegetation characteristics was species-specific. We found that there was not one attribute that determined bird occupancy across a majority of species (Table 1, Figs. 1 and 2). However, Canopy Height at 100m was the attribute that showed slightly higher effects, both positive and negative over a higher number of species (37, n = 38) in three out of four sampling seasons (Table 1, Figs. 1 and 2), followed by Canopy Height at 30m. A loss of Above Ground Biomass at 30 m could diminish occupancy probabilities for 12 species, such as the Long-tailed Manakin and Golden-olive Woodpecker (Figs.1 and 2)

Species occupancy probabilities

We found a positive relationship between Canopy Height at 100 m with those species that make use of forest, understory, and riparian habitats (Fig. 3). Low canopy height result in extremely low occupancy probabilities for species such as *Chiroxiphia linearis* (Long-tailed Manakin) and *Catharus aurantiirostris* (Orange-billed Nightingale-Thrush) that are understory inhabitants (Fig 3). Forest-related species showed an increase in their occupancy probability up to 50% between 10 m and 1 5m Canopy heights (Fig. 3). The opposite can be noticed when looking at the occupancy probability of forest avoidant species such as *Quiscalus mexicanus* (Great-tailed Grackle) (Fig. 4). In the case of some migratory species, occupancy probability increased as attributes related to the coffee plots and farms (i.e., CH30 and AGB100) increased (Fig. 5). However, most migratory species detected did not have enough detections to be modelled. Above Ground Biomass at 30 m proved to predict increasing occupancy probabilities for many common species like: *Megarynchus pitangua*

(Boat-billed Flycatcher), *Tiaris Olivaceus* (Yellow-faced Grassquit), *Pionus Senilis* (White-crowned Parrot), *Myiarchus tuberculifer* (Dusky-capped Flycatcher), and *Patagioenas flavirostris* (Red-billed Pigeon) (Fig.1 and Fig. 2).

Discussion

Results show that for most species, Canopy Height at 100 m was the attribute that predicted occupancy probability, Canopy Height is correlated to vegetation complexity (McElhinny et al., 2005; Zellweger et al., 2013). Therefore, higher, or lower vegetation complexity is one of the main causes of bird species occurrence inside productive agricultural landscapes (Singh et al., 2017; Céspedes & Bayly, 2019), as we expected. Above Ground Biomass was also a useful feature to predict occupancy probabilities, specially at a plot level of 30 m, for common species. This is valuable information because common species contribute to species richness patterns, provide information about the quality of habitat since they are affected differently by landscape changes than rare species (Van Schalkwyk et al., 2019), and could be endangered in the future if we don´t pay attention to their population behaviors (Lindenmayer et al., 2011). Conservation of endangered and common, but not less important species, depends not only on the preservation of national parks but on all the other remaining habitats. To increase the presence of forest related bird species outside conservation sites, and to provide safe passage and mobility for migratory and resident birds, productive landscapes should become a safe place of transit and foraging for those species by maintaining different strata of vegetation and a relatively high and diverse biomass coverage.

Relationships between species occupancy and vegetation attributes

Species that have been described as users of secondary growing habitats and rural zones such as *C. linearis* (Long-tailed Manakin) and *C. aurantirostriis* (Orange-billed Nightingale-Thrush) (Stiles & Skutch, 1989) have higher occupation probabilities around 10 m Canopy Height during the dry season (Fig.1), which is the average Canopy Height of the point counts we had on coffee plots. Species that are considered common within the forest and forest borders such as *Cyanerpes cyaneus* (Red-legged Honeycreeper), and

Euphonia luteicapilla (Yellow-crowned Euphonia) also increase their occupation probability as Canopy Height increases. This species and others might be observed crossing or even feeding at coffee plantations; however, they benefit from forest patches to rest, nest, mate, or forage (Stiles & Skutch, 1989., Ruiz-Gutierrez et al., 2010). Some species that have been classified as adaptable to habitat change such as *Campilorhynchus rufinucha (*Rufous-naped Wren), and *Tytira semifasciata* (Masked Tityra) because they use mostly open habitats with isolate trees and bushes, dry forest, and forest edges (Stiles, 1985; Stiles & Skutch, 1989), also show a decline in the occupation probability as Canopy Height at 100 diminish. However, species that explode degraded habitats such as *Quiscalus mexicanus* (Great-tailed Grackle), which increased its distribution in Costa Rica as deforestation expanded in the twentieth century (Stiles & Skutch, 1989), decreased its occupation probability as Canopy Height and Above Ground Biomass values decreases.

Several insectivorous birds, both resident and migratory, are known to require high canopy trees for food and shelter, including *Cardelina canadensis* (Canada Warbler) a specie with populations decline (Céspedes & Bayly, 2018; Narango et al., 2019). Additionally, we observed this pattern also for species such as *Setophaga petechia* (Yellow Warbler) and *Leiothlypis peregrina* (Tennessee Warbler), where occupancy probability increased as CH30 and AGB100 increased, respectively. It was common to observe *Setophaga pensylvanica* (Chestnut-sided Warbler) in high trees (over 15m). Nevertheless, we must notice that in most farms the highest trees available were introduced species of *Eucalyptus,* which is used as a wood source (Schaller et al., 2003).

Thresholds of vegetation attributes and management

Increasing canopy height over 10 to 15 m in coffee farms could increase the occupancy probability of bird species (e.g., *Lepidocolaptes souleyetii, Zimmerius parvus, Habia rubica, Colaptes rubiginosus, Cyanerpes cyaneus*). This increase in tree heights is possible for most coffee plantations given they have already trees that could grow to that height if owners and managers did not cut all the top branches. Above Ground Biomass values under 2.0 MgC-ha decrease occupancy probabilities for most birds. These low values sustained over time are usually related to pastures (González-Jaramillo, et al., 2018); but also occur when pruning an entire plot of coffee because almost all vegetation cover is removed. As important as Canopy Height and Above Ground Biomass values, is the composition of plant species that result in those values, retaining shade-trees of native varieties has been proven important for supporting high functional diversity in America, Asia, and Africa coffee plantations (Gonzalez et al., 2020; Variar et al., 2021; Chaves-Elizondo, 2022; Kammerichs-Berke et al., 2022). Consequently, higher values of both measurements need to be provided mostly by the use of native plants and trees.

Recommendations

The vegetation attributes we explore in this study are related to management practices within the coffee farms. Shade-trees and life fences contribute to increasing the average Canopy Height of a plot. Above Ground Biomass is related to the occurrence of shade-trees and coffee plants and the methods used to prune both, because this practice changes the biomass present between seasons and/or over the years. Based on this, and information reported for the same farms regarding tree usage by birds (Chaves-Elizondo, 2022), we can list threerecommendations to improve vegetation complexity on the coffee farms. (1) Increasing tree diversity used for shadow, implementing tall species that benefit migratory warblers (e.g., *Cordia alliodora*). (2) Planting native bushes or middle-height fruiting trees (10-15m) as part of life fences (ej. *Erythrina fusca, Myrcine coriacia*) to increase overall Canopy Height. (3) Practice selective pruning of shade-trees and coffee plants, where not all plants in a plot are pruned in the same season and shade-trees are allowed to retain some branches to avoid drops in Above Ground Biomass.

Conclusions

We consider that combining the integration of trees within the coffee plots, and investing in reforestation of the river banks and forest remnants within the farm and on neighboring land is the best approach to increase vegetation complexity at the coffee plantations and landscape levels. This would require the involvement of stakeholders outside of the coffee private sector, such as the community members and farmers managing other plantations around the coffee plantations areas. For future evaluations, it would be valuable to include covariates from the field such as the proportion of shade-trees vs coffee area, diversity of tree species in life fences and on the farm in general, and pruning practices. Then modelling the response of birds to these management practices for different coffee regions and including multi specie models to explore the community-level response. Here we identified thresholds of vegetation complexity that can inform and evaluate management practices on coffee farms, but mainly, we added a grain of evidence regarding the importance of productive agricultural landscapes for the objectives of biodiversity conservation.

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Tables and figures

Table 1 Relationships between occupancy of bird species and habitat attributes among seasons. Vegetation attributes that influenced species occupancy were determined through model selection. The number of species affected by each attribute is given for Dry and Rainy season of both years.

Season	Vegetation attribute	Total Spp 2020	Spp with a positive effect 2020	Spp with a negative effect 2020	Total Spp 2021	Spp with a positive effect 2021	Spp with a negative effect 2021
Dry	**CH30**	**9**	3	6	**12**	4	8
	CH100	**14**	2	12	**1**	0	1
	AGB30	**4**	2	2	**8**	2	6
	AGB100	**3**	0	3	**0**	0	0
Rainy	**CH30**	**13**	1	12	**4**	3	2
	CH100	**17**	0	17	**1**	0	1
	AGB30	**5**	2	3	**4**	2	2
	AGB100	**1**	0	1	**2**	1	1

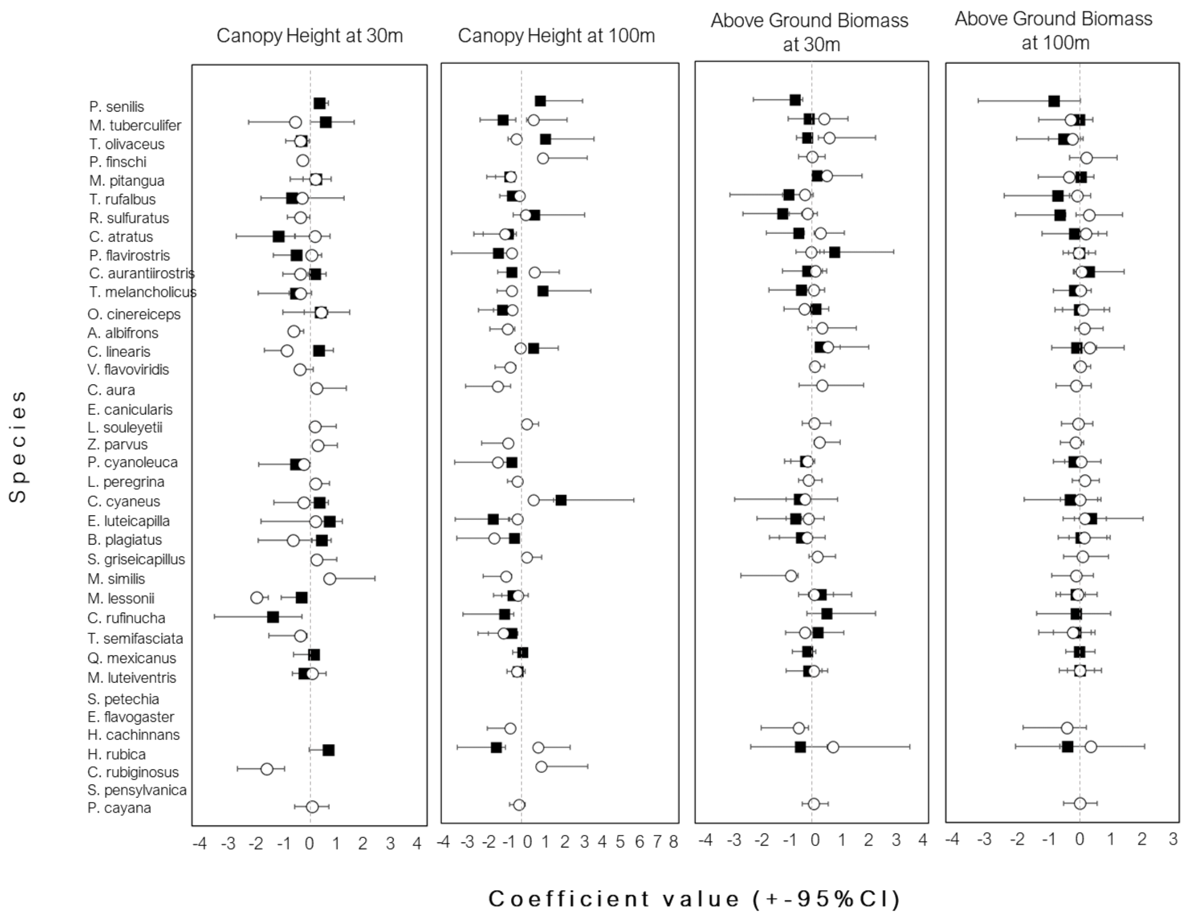

Fig. 1. Regression coefficients derived from models that examine variation in occupancy probabilities of different bird species as functions of four vegetation attributes during dry season. Dashed lines indicate a regression coefficient equal to zero. Dark squares correspond to 2020 and white dots correspond to 2021. Whiskers correspond to confidence intervals, when overlapping with zero indicates no effect or lack of significance.

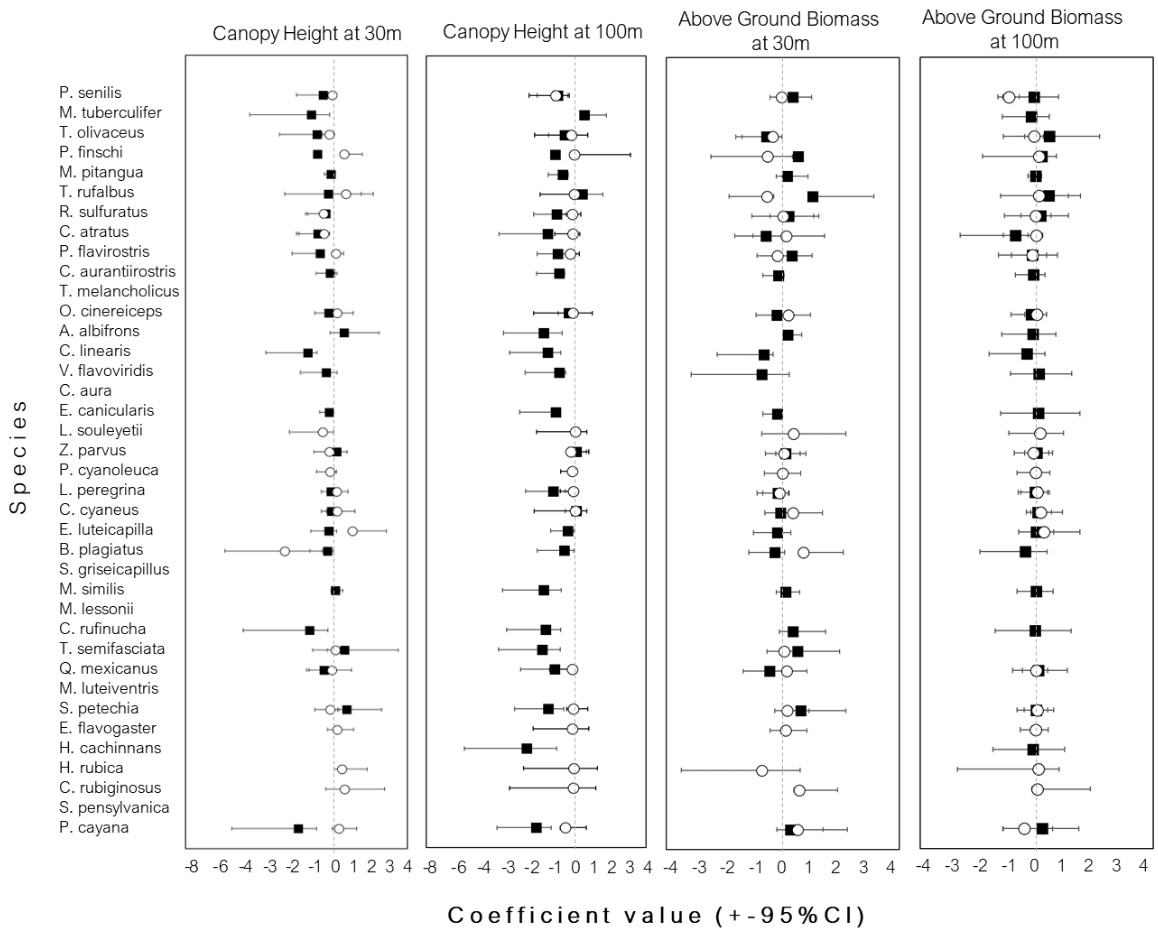

Fig. 2. Regression coefficients derived from models that examine variation in occupancy probabilities of different bird species as functions of four vegetation attributes during rainy season. Dashed lines indicate a regression coefficient equal to zero. Dark squares correspond to 2020 and White dots correspond to 2021. Whiskers correspond to confidence intervals, when overlapping with zero indicates no effect or lack of significance.

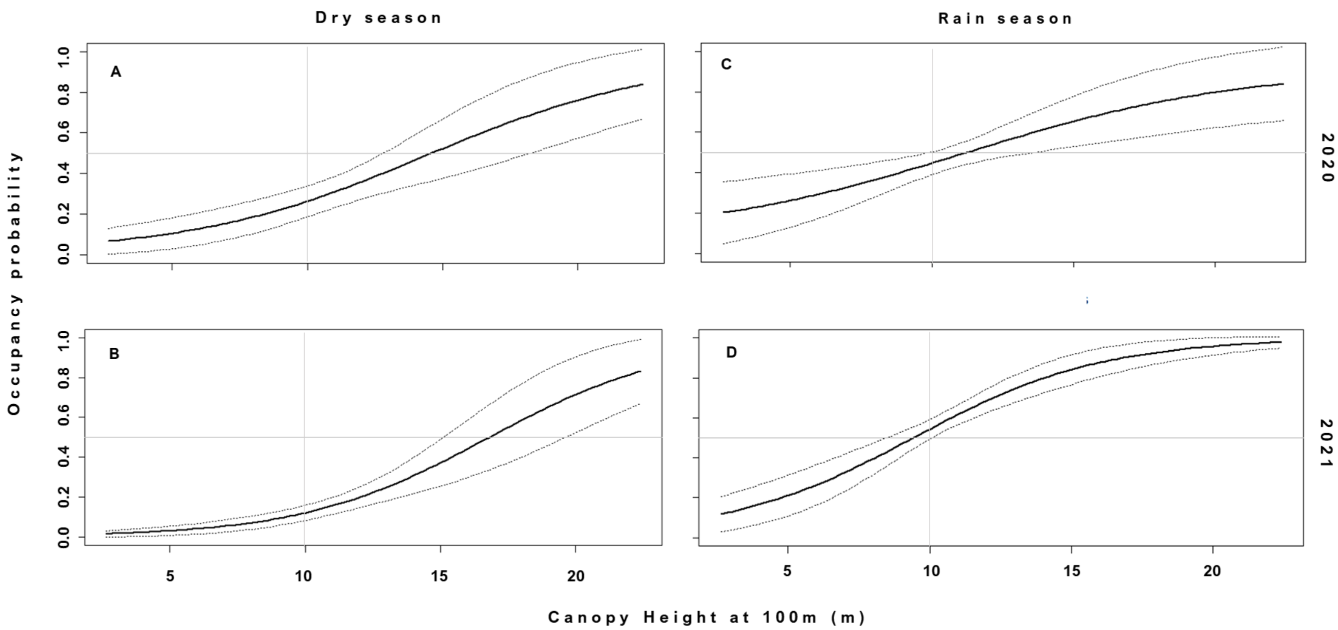

Fig. 3. Predicted relationships between occupancy probabilities of two shrub and forest inhabitant species *Chiroxiphia linearis* (Long-tailed Manakin) (A,B)during the dry season and *Catharus aurantiirostris* (Orange-billed Nightingale-Thrush)(C,D) during the rainy season, with Canopy Height at 100m. The horizontal gray line shows a 50% probability threshold. The vertical gray line shows the average value of that attribute for the coffee plots.

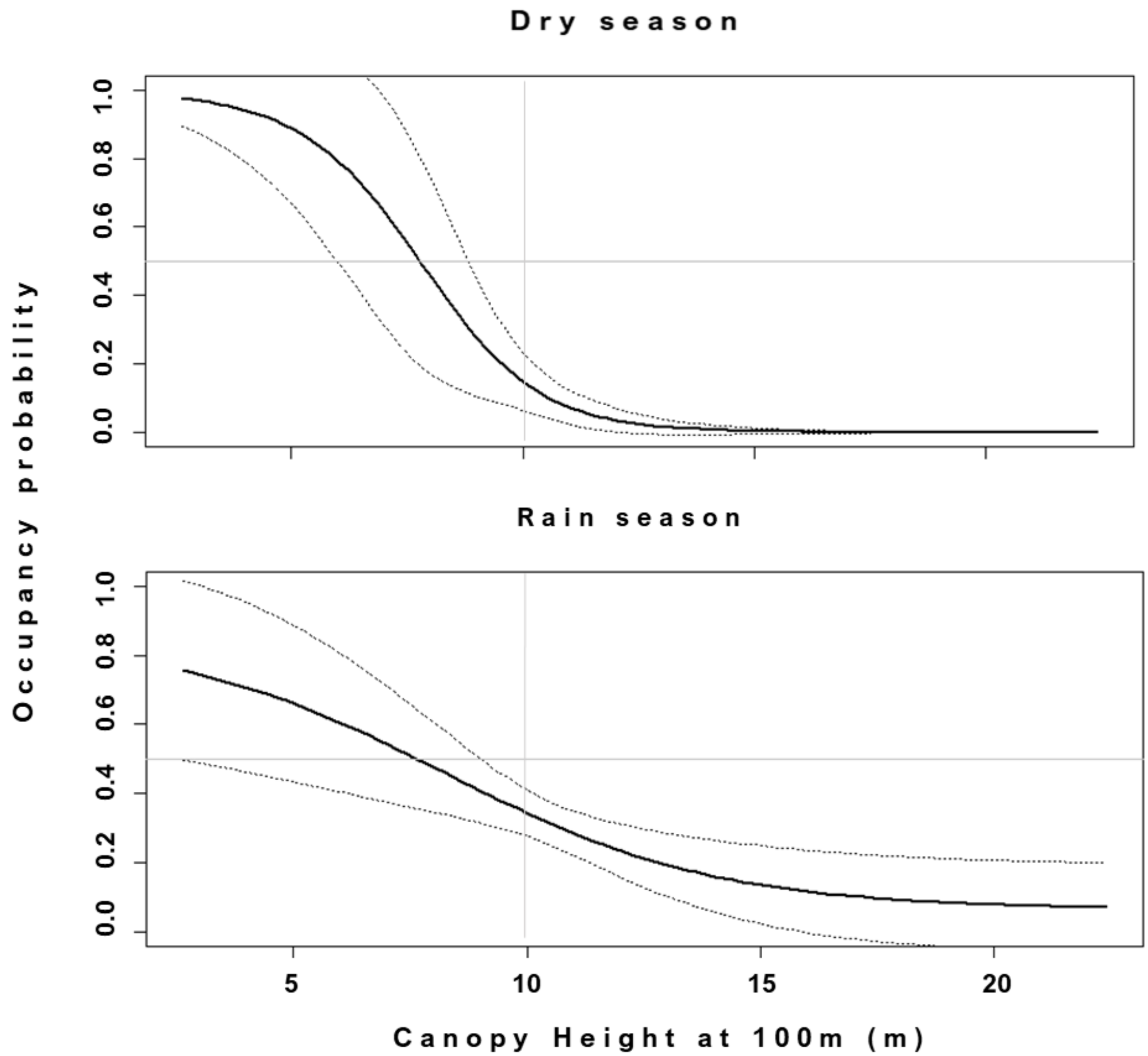

Fig. 4. Predicted relationships between occupancy probabilities of a forest avoidant specie, *Quiscalus mexicanus* (Great-tailed Grackle) with Canopy Height at 100m in both seasons for the year 2020. The horizontal gray line shows a 50% probability threshold. The vertical gray line shows the average value of that attribute for the coffee plots.

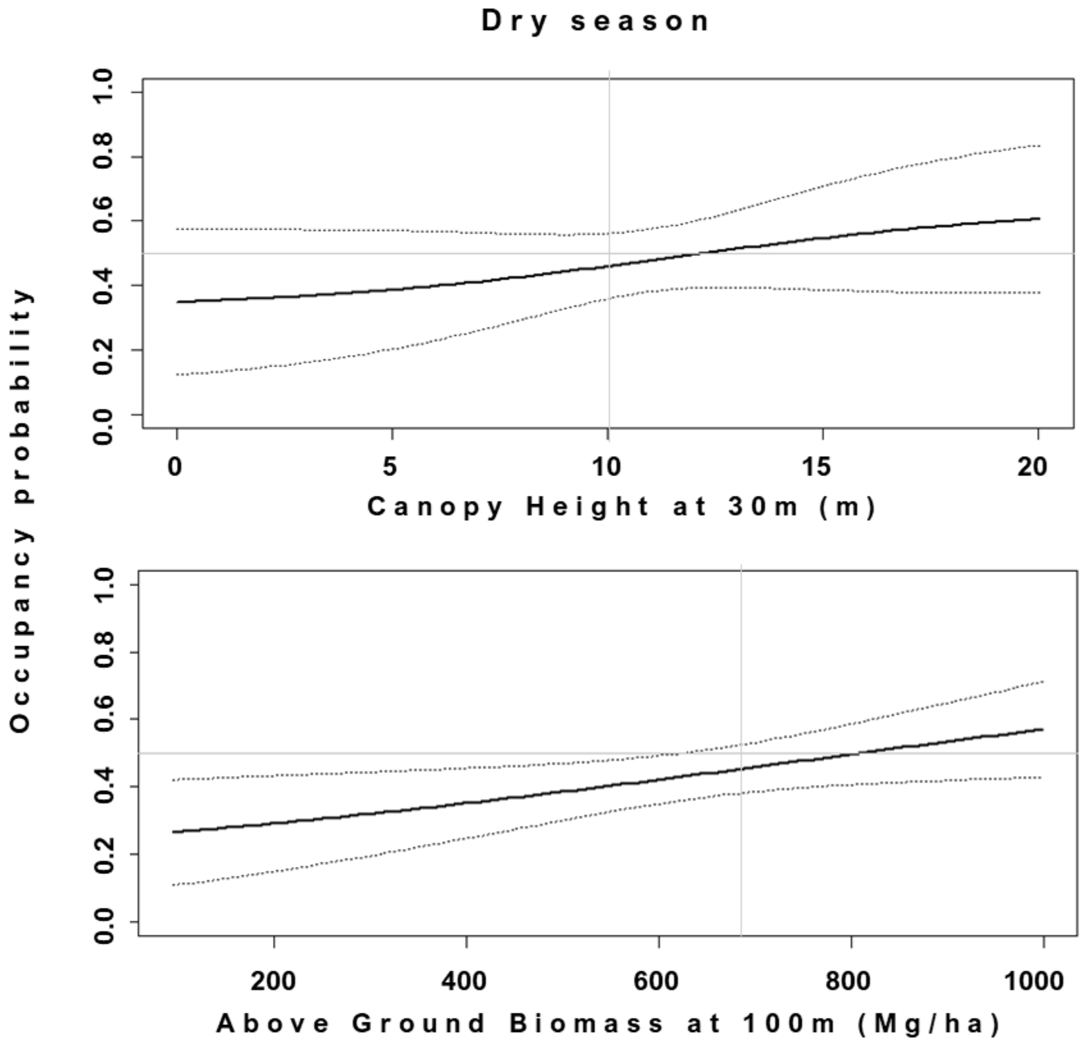

Fig. 5. Predicted relationships between occupancy probabilities of two migratory species, *Setophaga petechia* (Yellow Warbler) with Canopy Height at 30m and *Leiothlypis peregrina* (Tennessee Warbler) with Above ground biomass at 100m during dry season of 2020. The horizontal gray line shows a 50% probability threshold. The vertical gray line shows the average value of that attribute for the coffee plots.

Appendix A. Total list of species observed between 2020 and 2021.

Scientific Name	Common English name	Number of individuals	Relative abundance
TINAMIFORMES			
Tinamidae (1)			
Crypturellus soui	Little Tinamou	53	0.213%
ANSERIFORMES			
Anatidae (1)			
Cairina moschata	Muscovy Duck	1	0.004%
GALLIFORMES			
Cracidae (3)			
Ortalis cinereiceps	Gray-headed Chachalaca	**312**	1.254%
Penelope purpurascens	Crested Guan	4	0.016%
Chamaepetes unicolor	Black Guan	8	0.032%
Odontophoridae (3)			
Dendrortyx leucophrys	Buffy-crowned Wood-Partridge	8	0.032%
Colinus leucopogon	Spot-bellied Bobwhite		
Colinus cristatus	Crested Bobwhite	5	0.020%
COLUMBIFORMES			
Columbidae (9)			
Patagioenas flavirostris	Red-billed Pigeon	**401**	1.611%
Patagioenas fasciata	Band-tailed Pigeon	1	0.004%
Patagioenas subvinacea	Ruddy Pigeon		
Patagioenas nigrirostris	Short-billed Pigeon	5	0.020%
Columbina inca	Inca Dove	65	0.261%
Columbina passerina	Common Ground Dove	2	0.008%
Columbina talpacoti	Ruddy Ground Dove	3	0.012%
Leptotila verreauxi	White-tipped Dove	682	2.740%
Zenaida asiatica	White-winged Dove	51	0.205%
CUCULIFORMES			
Cuculidae (3)			
Crotophaga sulcirostris	Groove-billed Ani	60	0.241%
Tapera naevia	Striped Cuckoo	15	0.060%
Piaya cayana	Squirrel Cuckoo	**104**	0.418%
CAPRIMULGIFORMES			
Caprimulgidae (2)			
Chordeiles acutipennis	Lesser Nighthawk	1	0.004%
Nyctidromus albicollis	Common Pauraque	14	0.056%
APODIFORMES			
Apodidae (2)			
Streptoprocne zonaris	White-collared Swift	26	0.104%

Chaetura vauxi	Vaux's Swift	20	0.080%
Trochilidae (16)			
Phaethornis guy	Green Hermit	47	0.189%
Phaethornis longirostris	Long-billed Hermit	2	0.008%
Phaethornis striigularis	Stripe-throated Hermit	18	0.072%
Anthracothorax prevostii	Green-breasted Mango	2	0.008%
Heliodoxa jacula	Green-crowned Brilliant	6	0.024%
Heliomaster longirostris	Long-billed Starthroat	3	0.012%
Heliomaster constantii	Plain-capped Starthroat	28	0.113%
Lampornis calolaemus	Purple-throated Mountain-gem	2	0.008%
Philodice bryantae	Magenta-throated Woodstar	3	0.012%
Archilochus colubris	Ruby-throated Hummingbird	3	0.012%
Cynanthus canivetii	Canivet's Emerald	37	0.149%
Campylopterus hemileucurus	Violet Sabrewing	4	0.016%
Microchera cupreiceps	Coppery-headed Emerald	3	0.016%
Eupherusa eximia	Stripe-tailed Hummingbird	6	0.024%
Saucerottia cyanura	Blue-tailed Hummingbird	**134**	0.538%
Amazilia tzacatl	Rufous-tailed Hummingbird	1029	4.135%
GRUIFORMES			
Rallidae (3)			
Aramides cajaneus	Gray-cowled Wood-Rail	75	0.301%
Aramides albiventris	Russet-naped Wood-Rail	8	0.032%
Laterallus albigularis	White-throated Crake	6	0.024%
CHARADRIIFORMES			
Charadriidae (1)			
Vanellus chilensis	Southern Lapwing	5	0.020%
EURYPYGIFORMES			
Eurypygidae (1)			
Eurypyga helias	Sunbittern	3	0.012%
PELECANIFORMES			
Ardeidae (5)			
Ardea alba	Great Egret	2	0.008%
Bubulcus ibis	Cattle Egret	20	0.080%
Coragyps atratus	Black Vulture	**411**	1.651%
Cathartes aura	Turkey Vulture	**245**	0.984%
Ardea herodias	Great Blue heron	2	0.008%
ACCIPITRIFORMES			
Accipitridae (9)			
Elanus leucurus	White-tailed Kite	1	0.004%
Elanoides forficatus	Swallow-tailed Kite	9	0.036%
Accipiter bicolor	Bicolored Hawk	12	0.048%
Pseudastur albicollis	White Hawk	4	0.016%

Buteo plagiatus	Gray Hawk	**156**	0.627%
Buteo platypterus	Broad-winged Hawk	26	0.104%
Buteo brachyurus	Short-tailed Hawk	43	0.173%
Buteo albonotatus	Zone-tailed Hawk	1	0.004%
Buteo jamaicensis	Red-tailed Hawk	2	0.008%
STRIGIFORMES			
Strigidae (2)			
Megascops choliba	Tropical Screech-Owl	1	0.004%
Glaucidium brasilianum	Ferruginous Pygmy-Owl	16	0.064%
TROGONIFORMES			
Trogonidae (2)			
Trogon caligatus	Gartered Trogon	41	0.165%
Trogon collaris	Collared Trogon	11	0.044%
CORACIIFORMES			
Momotidae (1)			
Momotus lessonii	Lesson's Motmot	**140**	0.563%
Alcedinidae (2)			
Megaceryle torquatus	Ringed Kingfisher	18	0.072%
Chloroceryle americana	Green Kingfisher	2	0.008%
PICIFORMES			
Semnornithidae (1)			
Semnornis frantzii	Prong-billed Barbet	4	0.016%
Ramphastidae (4)			
Aulacorhynchus prasinus	Northern Emerald-Toucanet	52	0.209%
Pteroglossus torquatus	Collared Aracari	5	0.020%
Pteroglossus frantzii	Fiery-billed Aracari	2	0.008%
Ramphastos sulfuratus	Keel-billed Toucan	**437**	1.756%
Picidae (5)			
Melanerpes hoffmannii	Hoffmann's Woodpecker	675	2.712%
Dryobates fumigatus	Smoky-brown Woodpecker	6	0.024%
Colaptes rubiginosus	Golden-olive Woodpecker	**107**	0.430%
Dryocopus lineatus	Lineated Woodpecker	78	0.313%
Campephilus guatemalensis	Pale-billed Woodpecker	3	0.012%
FALCONIFORMES			
Falconidae (4)			
Micrastur semitorquatus	Collared Forest-Falcon	3	0.012%
Caracara plancus	Crested Caracara	11	0.044%
Milvago chimachima	Yellow-headed Caracara	15	0.060%
Herpetotheres cachinnans	Laughing Falcon	**111**	0.446%
PSITTACIFORMES			
Psittacidae (7)			
Eupsittula canicularis	Orange-fronted Parakeet	**232**	0.932%
Psittacara finschi	Crimson-fronted Parakeet	**452**	1.816%
Brotogeris jugularis	Orange-chinned Parakeet	66	0.265%
Pyrilia haematotis	Brown-hooded Parrot	13	0.052%

Pionus senilis	White-crowned Parrot	**496**	1.993%
Amazona albifrons	White-fronted Parrot	**311**	1.250%
Amazona autumnalis	Red-lored Parrot	2	0.008%
PASSERIFORMES			
Pipridae (1)			
Chiroxiphia linearis	Long-tailed Manakin	**277**	1.113%
Cotingidae (8)			
Procnias tricarunculatus	Three-wattled Bellbird	14	0.056%
Tityridae (3)			
Tityra semifasciata	Masked Tityra	**137**	0.550%
Tityra inquisitor	Black-crowned Tityra	3	0.012%
Pachyramphus aglaiae	Rose-throated Becard	49	0.197%
Tyrannidae (23)			
Mionectes olivaceus	Olive-striped Flycatcher	1	0.004%
Todirostrum cinereum	Common Tody-Flycatcher	58	0.233%
Rhynchocyclus brevirostris	Eye-ringed Flatbill	7	0.028%
Tolmomyias sulphurescens	Yellow-olive Flycatcher	76	0.305%
Camptostoma imberbe	Northern Beardless-Tyrannulet	4	0.016%
Elaenia flavogaster	Yellow-bellied Elaenia	**115**	0.462%
Zimmerius parvus	Mistletoe Tyrannulet	**214**	0.860%
Mitrephanes phaeocercus	Tufted Flycatcher	1	0.004%
Contopus cooperi	Olive-sided Flycatcher	2	0.008%
Contopus sordidulus	Western Wood-Pewee	41	0.165%
Contopus virens	Eastern Wood-Pewee	46	0.185%
Contopus cinereus	Tropical Pewee	11	0.044%
Empidonax flaviventris	Yellow-bellied Flycatcher	15	0.060%
Empidonax flavescens	Yellowish Flycatcher	3	0.012%
Sayornis nigricans	Black Phoebe	15	0.060%
Myiarchus tuberculifer	Dusky-capped Flycatcher	**493**	1.981%
Pitangus sulphuratus	Great Kiskadee	599	2.407%
Megarynchus pitangua	Boat-billed Flycatcher	448	1.800%
Myiozetetes similis	Social Flycatcher	**149**	0.599%
Myiodynastes maculatus	Streaked Flycatcher	4	0.016%
Myiodynastes luteiventris	Sulphur-bellied Flycatcher	**122**	0.490%
Legatus leucophaius	Piratic Flycatcher	40	0.161%
Tyrannus melancholicus	Tropical Kingbird	**324**	1.302%
Thamnophilidae (1)			
Thamnophilus doliatus	Barred Antshrike	18	0.072%
Rhinocryptidae (1)			
Scytalopus argentifrons	Silvery-fronted Tapaculo	5	0.020%
Furnariidae (5)			
Sittasomus griseicapillus	Olivaceous Woodcreeper	**150**	0.603%
Xiphorhynchus susurrans	Cocoa Woodcreeper	5	0.020%

Xiphorhynchus erythropygius	Spotted Woodcreeper	2	0.008%
Lepidocolaptes souleyetii	Streak-headed Woodcreeper	**219**	0.880%
Dendroma rufa	Buff-fronted Foliage-gleaner	1	0.004%
Vireonidae (5)			
Pachysylvia decurtata	Lesser Greenlet	40	0.161%
Vireo flavifrons	Yellow-throated Vireo	43	0.173%
Vireo philadelphicus	Philadelphia Vireo	13	0.052%
Vireo olivaceus	Red-eyed Vireo	2	0.008%
Vireo flavoviridis	Yellow-green Vireo	**249**	1.001%
Corvidae (2)			
Calocitta formosa	White-throated Magpie-Jay	4	0.016%
Psilorhinus morio	Brown Jay	1081	4.344%
Hirundinidae (3)			
Pygochelidon cyanoleuca	Blue-and-white Swallow	**178**	0.715%
Stelgidopteryx serripennis	Northern Rough-winged Swallow	42	0.169%
Hirundo rustica	Barn Swallow	1	0.004%
Troglodytidae (10)			
Microcerculus philomela	Nightingale Wren	4	0.016%
Microcerculus marginatus	Scaly-breasted Wren	3	0.012%
Pheugopedius rutilus	Rufous-breasted Wren	755	3.034%
Cantorchilus modestus	Cabanis's Wren	1526	6.132%
Henicorhina leucosticta	White-breasted Wood-Wren	5	0.020%
Henicorhina leucophrys	Gray-breasted Wood-Wren	3	0.012%
Thryophilus rufalbus	Rufous-and-white Wren	**446**	1.792%
Campylorhynchus rufinucha	Rufous-naped Wren	**138**	0.555%
Troglodytes aedon	House Wren	686	2.756%
Troglodytes ochraceus	Ochraceous Wren	1	0.004%
Mimidae (1)			
Mimus gilvus	Tropical Mockingbird	1	0.004%
Turdidae (8)			
Myadestes melanops	Black-faced Solitaire	1	0.004%
Catharus aurantiirostris	Orange-billed Nightingale-Thrush	**386**	1.551%
Catharus fuscater	Slaty-backed Nightingale-Thrush	5	0.020%
Catharus mexicanus	Black-headed Nightingale-Thrush	1	0.004%
Catharus ustulatus	Swainson's Thrush	49	0.197%
Hylocichla mustelina	Wood Thrush	1	0.004%
Turdus plebejus	Mountain Thrush	2	0.008%
Turdus grayi	Clay-colored Thrush	731	2.937%
Fringillidae (6)			
Chlorophonia elegantissima	Elegant Euphonia	3	0.012%

Chlorophonia callophrys	Golden-browed Chlorophonia	62	0.249%
Euphonia affinis	Scrub Euphonia	1	0.004%
Euphonia luteicapilla	Yellow-crowned Euphonia	**161**	0.647%
Euphonia hirundinacea	Yellow-throated Euphonia	685	2.752%
Spinus psaltria	Lesser Goldfinch	1	0.004%
Passerellidae (3)			
Zonotrichia capensis	Rufous-collared Sparrow	60	0.241%
Melozone leucotis	White-eared Ground-Sparrow	626	2.515%
Melozone cabanisi	Cabanis's Ground-Sparrow	2	0.008%
Icteridae (10)			
Amblycercus holosericeus	Yellow-billed Cacique	2	0.008%
Psarocolius montezuma	Montezuma Oropendola	606	2.435%
Icterus prosthemelas	Black-cowled Oriole	4	0.016%
Icterus pectoralis	Spot-breasted Oriole	2	0.008%
Icterus galbula	Baltimore Oriole	67	0.269%
Agelaius phoeniceus	Red-winged Blackbird	2	0.008%
Molothrus aeneus	Bronzed Cowbird	6	0.024%
Molothrus oryzivorus	Giant Cowbird	1	0.004%
Dives dives	Melodious Blackbird	629	2.527%
Quiscalus mexicanus	Great-tailed Grackle	**123**	0.494%
Parulidae (21)			
Seiurus aurocapilla	Ovenbird	1	0.004%
Parkesia motacilla	Louisiana Waterthrush	1	0.004%
Parkesia noveboracensis	Northern Waterthrush	8	0.032%
Vermivora chrysoptera	Golden-winged Warbler	8	0.032%
Mniotilta varia	Black-and-white Warbler	18	0.072%
Leiothlypis peregrina	Tennessee Warbler	**171**	0.687%
Geothlypis poliocephala	Gray-crowned Yellowthroat	35	0.141%
Geothlypis philadelphia	Mourning Warbler	1	0.004%
Geothlypis formosa	Kentucky Warbler	1	0.004%
Setophaga ruticilla	American Redstart	6	0.024%
Setophaga pitiayumi	Tropical Parula	2	0.008%
Setophaga fusca	Blackburnian Warbler	4	0.016%
Setophaga petechia	Yellow Warbler	**116**	0.466%
Setophaga pensylvanica	Chestnut-sided Warbler	**105**	0.422%
Setophaga virens	Black-throated Green Warbler	5	0.020%
Myiothlypis fulvicauda	Buff-rumped Warbler	1	0.004%
Basileuterus delattrii	Chestnut-capped Warbler	1315	5.284%
Basileuterus culicivorus	Golden-crowned Warbler	6	0.024%
Basileuterus melanotis	Costa Rican Warbler	2	0.008%
Cardellina pusilla	Wilson's Warbler	40	0.161%
Myioborus miniatus	Slate-throated Redstart	35	0.141%

Cardinalidae (4)			
Piranga rubra	Summer Tanager	75	0.301%
Habia rubica	Red-crowned Ant-Tanager	**107**	0.430%
Pheucticus ludovicianus	Rose-breasted Grosbeak	2	0.008%
Cyanoloxia cyanoides	Blue-black Grosbeak	7	0.028%
Thraupidae (17)			
Thraupis episcopus	Blue-gray Tanager	515	2.069%
Thraupis palmarum	Palm Tanager	19	0.076%
Stilpnia larvata	Golden-hooded Tanager	26	0.104%
Tangara gyrola	Bay-headed Tanager	1	0.004%
Tangara icterocephala	Silver-throated Tanager	16	0.064%
Volatinia jacarina	Blue-black Grassquit	27	0.108%
Ramphocelus passerinii	Scarlet-rumped Tanager	34	0.137%
Cyanerpes cyaneus	Red-legged Honeycreeper	**167**	0.671%
Dacnis cayana	Blue Dacnis	1	0.004%
Coereba flaveola	Bananaquit	1	0.004%
Tiaris olivaceus	Yellow-faced Grassquit	**490**	1.969%
Sporophila corvina	Variable Seedeater	12	0.048%
Sporophila morelleti	Morelet’s Seedeater	1	0.004%
Sporophila nigricollis	Yellow-bellied Seedeater	1	0.004%
Saltator atriceps	Black-headed Saltator	53	0.213%
Saltator maximus	Buff-throated Saltator	675	2.712%
Saltator grandis	Cinnamon-bellied Saltator	**158**	0.635%
Total		24886	100.000%

Capítulo 2. Changes in bird detection in response to prune and agrochemicals application on coffee farms

Abstract

Ecosystem services provided by birds using coffee plantations, such as pollination and insect control, are well documented. However, we still need to explore the effect of agricultural practices of coffee plantationson those birds. Here we used passive recorders to detect six bird species that actively use coffee plots for forage, nesting, and refuge andestimated the changes in bird detection in response to pruning and agrochemicals applications on coffee plantations in Costa Rica. Birds that forage on the ground, like White-eared Ground-Sparrow (*Melozone leucotis*), were affected by the pruning of coffee plants more evidently than other species. Agrochemical applications affect bird detection in general, but it variates between species. Differences between species in the responses are explained by their feeding and behavior habits. Identify the way that birds react to these practices allowed us to suggest six actions to decrease the negative effects of chemical application and pruning of coffee plants. Evaluating the production and management practices on coffee farms and actively improving them is an effort to be addressed by producers and commercialization companies if the goal is to co-exist with wildlife in high biodiversity regions.

Key words: sustainable coffee, fungicides, herbicides, pest control, co-existing

Industrial agriculture is focused to increase production, maintaining reasonable costs, and minimizing the outflow of resources (Nicol and Nicol, 2018). Practices and technologies such as irrigation systems, enhancement of plant varieties, fertilization and improvement of soils, and pest control are used to achieve more production (Puignau, 1995). However, many of those industrial agricultural practices have consequences for the environment, human health, and biodiversity (Gamboa, 2005; Lajmanovich et al., 2012; Segura, 2015).

In the cultivation of coffee, chemicals such as the insecticide chlorpyrifos are used to combat the coffee borer, *Hypothenemus hampei*, and other pests, and fungicides like pyraclostrobin and epoxiconazole are washed into surface waters, and aquifers when rains fall, causing pollution of other ecosystems (Soares et al., 2017; Hoff et al., 2019). The pesticide chlorpyrifos has the potential to bioaccumulate in bees and fish, affecting development, fertility, and survival (Thomas and Mansingh, 2002; Arroyo Rivera, 2022). This chemical also negatively affects neurological development and causes endocrine disruption in humans (Lee et al., 2004; Wesseling et al., 2006; Lee et al., 2007) and other animals. It can impede migratory birds' orientation and navigation ability, due to the disruption of acetylcholine transmission and other neurotoxic effects (Eng et al., 2017). This insecticide eliminates the borer, but also many other non-pests insects that are the food source for a large group of animals such as birds, reptiles, amphibians, and mammals (Chang et al., 2018).

Pruning and tree removal are other common practices in industrial agriculture that affects animals within field crops. In sugar cane and pineapple fields, it is required the complete removal of vegetation, which eliminates sites and resources used by animals to move or forage, causing the reproductive isolation of some species (Ripperger et al., 2015; Becca et al., 2017). However, in crops where vegetation cover is partially pruned, such as citrus fruits and shaded coffee, some animals can move and live using the remanent vegetation (Santos and Tellería, 2006; Estrada-Carmona et al, 2019).

In coffee fields, the management practices are conducted at specific times of the year (Vieira, 2008), when they may impact the habitat use by birds. In the coffee-growing region of the Western Valley of Costa Rica, the application of agrochemicals such as insecticides, nematicides, fungicides, and fertilizers occurs from June to September, in the first months of the rainy season (Barquero, 2013). They are applied by liquid atomization of the foliage, as the insecticides, and others are placed on the ground under each coffee plant, such as nitrogen. The application coincides with the end of the breeding season for many resident birds in tropical areas (Skutch, 1950), exposing the hatchlings to chemicals, which could affect them in the previously exposed ways.

The grain coffee harvest occurs between December to February (Haight, 2007), which coincides with the migratory season for North American birds at the summer late and the early autumn (Marra et al., 2006; Faaborg et al., 2010). After the harvest followsc the pruning of coffee plants in March and April, which coincides with the time when the migratory birds return to North America (February-March), and the beginning of the reproductive season for most Neotropical resident bird species (April-June) (Skutch, 1950). The noise caused by machinery, coupled with the loss of vegetation could affect the mating behavior and even nest survival of the resident birds, especially those nesting on coffee plants.

Understanding the use of agricultural fields by birds depending on the time of year and the practices applied will allow making management decisions to reduce the aforementioned impacts in productive landscapes. In forest plantations in Canada, maintaining tree aggregations in the harvest area increases the abundance of small mammals compared to keeping scattered trees (Sullivan and Sullivan, 2018). In rice fields in California, extending post-harvest flooding by three weeks significantly increased the habitat availability for different migratory birds (Sesser et al., 2018).

Besides conservation interests, assuring the presence of birds in cultivated lands can reduce crop damage and pest abundance while increasing crop yield (Dias-Siefer et al., 2021). The positive effect of birds on pest reduction in coffee plantations has been well documented (McMilligan et al., 2016; Chain-Guadarrama et al., 2019; Escobar-Ramirez, 2019; Martinez-Salinas et al. 2022). Therefore, our objective is to estimate changes in bird habitat use in response to the pruning of coffee plants after harvests and the application of agrochemicals on coffee plantations in Costa Rica. If coffee pruning and agrochemical applications affect negatively bird habitat use, we expect to observe less occurrence of bird species after pruning and agrochemical application.

Methods

Study site

I conducted the study in San Ramón, Alajuela province, Costa Rica (10° 13' N, 84° 35' W). The study site is located between 1,000 and 1,300 m a.s.l., between the basins of the Grande de San Ramón River and the Barranca River. The coffee plantations are located throughout the region in the districts of Santiago, San Rafael, Alfaro, Piedades Norte, Piedades Sur, and Concepción. The landscape is a mix of crops (coffee, tomato, sugar cane, ornamental plants, and smaller-scale subsistence crops of beans, corn, and oranges), grasslands, farms, and forest remnants. In addition, there are cattle pastures, poultry, and pig farms. Wooded areas remain along rivers, springs, and creeks, in the protected zones, or in abandoned properties, which have regenerated naturally. The areas of the individual properties range between 1 to 12.6 ha. The farms are owned and managed by families involving the work of several family members. All farms plant the *Coffee arabica* species, although they alternate in varieties such as Caturra, Catuaí, and others.

Survey

To make comparisons of bird habitat use before and after management practices, we deployed 20 Swift passive recording units (Cornell University Ornithology Laboratory). The recorders were placed one per farm, covering the area of a plot, in plantations that are within the AAA Sustainable Quality™ program of NESPRESSO and ECOM Agroindustrial (ECOM, 2019). Each recording unit was attached to a tree within a coffee plot at approximately 3 m above the ground. Recorders were scheduled to record continuously from 5:30 to 6:30 h which is the peak of the acoustic activity of the birds (Brown & Handford, 2003; Hilje & Sánchez-Azofeifa. 2017).

Each recorder was active for 45 days between January-March and 41 days between July-August 2021, to register bird vocalizations during seasons where different agricultural practices were applied. Farmers were asked to annotate the dates when each of the agricultural practices (agrochemicals application and pruning) were done and provide the list of products used as agrochemicals.

Bird species selection and identification

We selected six species using three criteria: (1) species frequently detected at the coffee plots on previous surveys, (2) species detected in the recordings, vocalizing on the coffee plots, and (3) resident species. The selected species were the Rufous-tailed Hummingbird (*Amazilia tzacatl),* Rufous-capped Warbler *(Basileuterus delatrii)*, White-tipped Dove *(Leptotila verreauxi),* Rufous-breasted Wren *(Pheugopedius rutilus),* White-eared Ground-Sparrow *(Melozone leucotis)*, and Cabanis's Wren *(Cantorchilus modestus)*. Using the Raven Pro 1.6 sound analysis software (Cornell University Laboratory of Ornithology) we annotated each time a specie was detected on 20 minutes of sampling within each hour of recording per day (see supplementary material).

Data analysis

We applied a Bayesian A/B test of proportions with an uninformative prior using the "Rjags" package (Plummer, 2022). We created a species-specific matrix of detection and non-detection events before (A) and after (B) each agricultural practice. We then modeled the relative frequency (Θ) of detecting the species in that habitat before (Θ_1) or after (Θ_2), using 5000 iterations and the highest density interval of 95%. Finally, we calculated the difference between those frequencies (Θ_1 - Θ_2) and the probability associated using a 95% credibility percentage.

Results

A total of 1 720 h of recordings were analyzed. Different kinds of agrochemicals were used during the second season, mostly fertilizers, herbicides, and fungicides (Table 1). White-eared ground sparrows had the higher mean detection during both seasons, followed by Rufous-capped Warbler and Rufous-breasted Wren during the second season (Table 2).

For the pruning season, the relative frequency of habitat use detection (Θ) was lower after pruning for all species, except for Rufous-capped Warbler (Figure 1). White-eared Ground-sparrow and White-tipped Dove relative frequencies of habitat use detection before pruning (Θ_1) were higher than the relative frequency of habitat use detection after pruning with over a 95% credibility interval (Θ_2; Figure 1). Rufous-breasted Wren, Rufous-tailed Hummingbird, and Cabanis´s Wren credibility interval values were below the 0.95 parameter that we used to determine differences; therefore, detection in both samplings were considered similar. For the Rufous-capped Warbler Θ_2 (after pruning) was higher than Θ_1 (before pruning) (Figure 1).

During the chemical application season, the relative frequency of habitat use detection (Θ) was lower after the application of agrochemicals, for all species (Figure 2). For White-eared Ground-sparrow, Rufous-breasted Wren, and Rufous-caped Warbler this season showed higher differences between Θ_1 and Θ_2 (Figure 2). White-tipped Dove Θ_1 has a 0.97 probability that was slightly higher than Θ_2 (Figure 2). The probabilities of Θ_1 were higher than Θ_2 for Cabanis´s Wren and Rufous-tailed Hummingbird and were below 0.95. Rufous-tailed Hummingbird was detected only in four of the 20 recorders during the second season.

Discussion

Changes in bird habitat use were detected after both practices, pruning and the application of agrochemicals. Herbicides reported in coffee farms, like Paraquat, and insecticides such as Chlorpyrifos, have been proven to be of high toxicity for birds and other vertebrates, causing deformities, and biochemical dysregulations (Thomas and Mansingh, 2002; Lee et al., 2004; Wesseling et al., 2006; Lee et al., 2007; Eng et al., 2017; Losdat et al., 2018; Arroyo Rivera, 2022). The Fungicide epoxyconazole which use has been prohibited in Europe since 1997, due to its high toxicity in water environments and hazardous effects on humans (European Commission 1997; Cocco 2002), and other vertebrates (Zhang et al., 2018), is used in Costa Rican coffee farms, under government approval (Barquero, 2013; MAG, 2022).

The decrease in bird habitat use after the application of agrochemicals was larger than the decrease detected after pruning. This difference may be caused by differences in how both practices are implemented. Agrochemical applications can be done by hand (for soil fertilizers) but are mostly done by hand pumps or motor pumps (for foliar fertilizers, fungicides, and herbicides), around the farm and trails (Barquero, 2013) generating disturbance due to noise, strong odors, irritation, and toxicity. However, pruning is done mostly by hand on the plot area producing low noise levels, for example.

Each species' habits and foraging strategies could help us explain the differences in the relative frequencies of habitat use detection. White-eared Ground-sparrow and Rufous-capped Warbler are species that forage within the coffee plots (Stiles and Skutch, 1989; Sandoval and Mennill, 2012), and are the two species that showed the greatest decrease in detection (Θ) after the application of agrochemicals. Rufous-caped Warbler forages on the coffee plant branches looking for insects (Stiles and Skutch, 1989), meanwhile, White-eared Ground-Sparrow feeds mostly on seeds and small insects on the ground (Stiles and Skutch, 1989; Sandoval and Mennill, 2012; Juárez et al., 2020). Probably both species decrease after chemical application because the abundance of insects in coffee plantations declines; therefore, they move to areas where insects are more abundant. Another possible cause for the decrease in the detection of birds is that high levels of chemicals in coffee plantations produce air pollution that repeals the species' presence.

White-eared Ground-sparrows and White-tipped Doves decrease in detection (ϴ) after pruning, because coffee plots lose vegetation density, and all the removed leaves and branches are left on the ground. Given that both species forage mostly on the ground looking for seeds (Stiles and Skutch, 1989), this practice increases the obstacles for foraging on the ground and opens the vegetation coverage, exposing these species to a more open area, leading birds to search food in other sites. However, for the Rufous-caped Warbler, detection (ϴ) values are higher after pruning. This warbler often forages for insects and perchs within the coffee branches, hence, the elimination of coffee branches may push itto forage to the trees, where the recorders increasing its detection or may increase the foraging rate after pruning, due to a higher activity of insects due to the disturbance.

The Roufus-breasted Wren which prefers tangled vines and scrubs at the coffee plot edges showed similar detection (ϴ) values before and after the pruning of the coffee plot but decreased after the application of agrochemicals. Conversely, Cabani´s Wren, a species that moves between the coffee plants and the surrounding bushes, lives fences, and riparian forests (Stiles and Skutch, 1989), showed similar detection before and after the application of agrochemicals and pruning. Rufous-tailed Hummingbirds showed similar detection values (ϴ) before and after pruning and a slight decrease after agrochemical applications, but it was not conclusive. This might respond to a reduction in the ability to detect this hummingbird due to the territorial behavior around flower patches (Stiles and Skutch, 1989), because flower patches are not that common within the coffee plots, and the blooming of coffee plants in this area is between April and June (period not included in the recordings).

The pruning and the application of chemicals on coffee plantations are basic practices around the world to increase coffee production. However, coffee consumers in developed-world markets prioritize sustainable labels that are pesticide-free (Gatti, et al. 2022), and that protect biodiversity. Therefore, finding a balance between coffee production, the adequate and regulated use of chemicals, and management practices such as pruning is a goal that still needs to be reached. This is vital for conservation purposes also because coffee farms are refuges for migratory and resident species (Philpott et al, 2008; González, et al, 2021). These species could include those with vulnerable populations, for instance, the Costa Rican endemic Cabanis's Ground-sparrow (*M. cabanisi*), whose distribution is restricted mostly to middle elevations thickets and coffee plantations, which are being lost by urbanization (Sandoval and Mennill, 2012; Juárez et al., 2020; Muñoz et al., 2021).

Management practices may be implemented to decrease the negative effects of agricultural practices and to increase biodiversity on coffee farms. Here we recommend six punctual actions (1) Consider using selective pruning or systematic cyclical pruning. This will keep the vegetal complexity of the farm higher than pruning the entire plot or farm (Azhar et al., 2013). (2) Consider pruning coffee farms before April or after June, to avoid the peak of the breeding season, including the Rufous-tailed hummingbird (Lindell and Smith, 2003). (3) Restrain from using herbicides to control weeds on the access trails and trails between plots, mowing is a good alternative. (4) Keep the dry leaf cover produced by the shade-trees and use mulch from the mowing within the coffee rows, this will retard other weed growth. (5) Consider leaving the weeds, there are many herbaceous species that are low-growing and have small roots that will not compete with the coffee and can provide other benefits such as food for birds and protecting soil from eroding (de Melo, et al. 2021). (6) Do not use higher concentrations of fungicides and fertilizers than recommended by the manufacturer or technician (Fuhrimann, 2019).

All six recommendations are intended to coffee production; however, they should be supported by coffee processers and commercialization companies. For example, stressing the importance of controlling concentrations of fungicides and fertilizers, facilitating this information, and working alongside producers to apply these improvements on the ground would be a step in the direction of sustainability. As next steps to keep exploring ways of reducing the impact of coffee production and get to co-exist with birds and other wildlife in highly biologically diverse regions we recommend: Exploring the time of recovery of species detection (ϴ) to the baseline level, the effect of different pruning techniques, or the differential effect of herbicides, insecticides, and fungicides and their different active components, latency and application methods.

Conclusions

This is an example of the kind of effects to look for when evaluating the production and management practices on coffee farms. The six species we used as examples showed different responses to both practices inside coffee plantations, being a good example of the complexity of bird community responses to coffee production and the necessity to analyze this practice's effect on other species and coffee plantation types. There is good evidence to infer that the agrochemical application methods and the pruning methods affected the relative frequency of habitat use detection. We have also tested the use of autonomous recorders to answer these questions and confirmed that they facilitate the data collection that other ways would have required an unrealistic number of resources. Finally, we were able to suggest six basic actions to decrease the negative effects of these practices while further research about recovery rates, pruning techniques, and chemical application techniques and products advances.

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Tables and figures

Table 1. List of agrochemicals applied during the study and the frequency they were mentioned by coffee producers.

Type	Description	Brand	Frequency
Fertilizer	Organic soil Fertilizer (manure)	-	0.15
	Chemical Soil fertilizer (N, P, K)	-	0.2
	Chemical foliar fertilizer (N, P, K)	Milagro	0.75
Herbicide	Methyl viologen	Paraquat	0.55
	Nicosulfuron 40 g/L	Quitamata 4	
Insecticide	Zeta-cypermethrin	Furia	1
	Chlorpyrifos	Tifón	
Fungicide	Validamicin A	Cepex	0.5
	Cyproconazole	Atemi	
	Epoxiconazole and Pyraclostrobin	Opera	

Table 2. Empirical detection mean, standard deviation, and standard error for six species of birds, before and after each productive practice. Here n represents the sample size and x the positive detections.

							95% HDI
Species	**Season**		**n**	**x**	**Mean**	**SD**	**SE**
Cabani´s wren	Pruning	Before	214	116	0.5414	0.0340	0.0003
		After	371	180	0.4851	0.0256	0.0002
	Agrochemical aplication	Before	103	45	0.4372	0.0480	0.0004
		After	307	122	0.3983	0.0277	0.0002
Rufous-breasted wren	Pruning	Before	217	84	0.0388	0.0325	0.0003
		After	368	136	0.3698	0.0252	0.0002
	Agrochemical aplication	Before	169	125	0.7371	0.0333	0.0003
		After	282	159	0.563	0.0293	0.0002
White-eared ground sparrow	Pruning	Before	214	137	0.6385	0.0322	0.0003
		After	371	211	0.5683	0.0256	0.0002
	Agrochemical aplication	Before	103	91	0.8761	0.0324	0.0003
		After	299	147	0.4915	0.0287	0.0002
Rufous-caped warbler	Pruning	Before	237	110	0.4636	0.0320	0.0003
		After	348	200	0.5737	0.0264	0.0002
	Agrochemical aplication	Before	103	86	0.8291	0.0363	0.0003
		After	315	135	0.4290	0.0274	0.0002
Red-tailed hummingbird	Pruning	Before	214	58	0.2732	0.0301	0.0002
		After	371	88	0.2385	0.0222	0.0002
	Agrochemical aplication	Before	26	4	0.1784	0.0711	0.0006
		After	138	13	0.0998	0.0254	0.0002
White-tipped dove	Pruning	Before	213	59	0.2792	0.0311	0.0003
		After	327	60	0.1855	0.0213	0.0002
	Agrochemical aplication	Before	138	28	0.2077	0.0343	0.0003
		After	231	30	0.1329	0.0223	0.0002

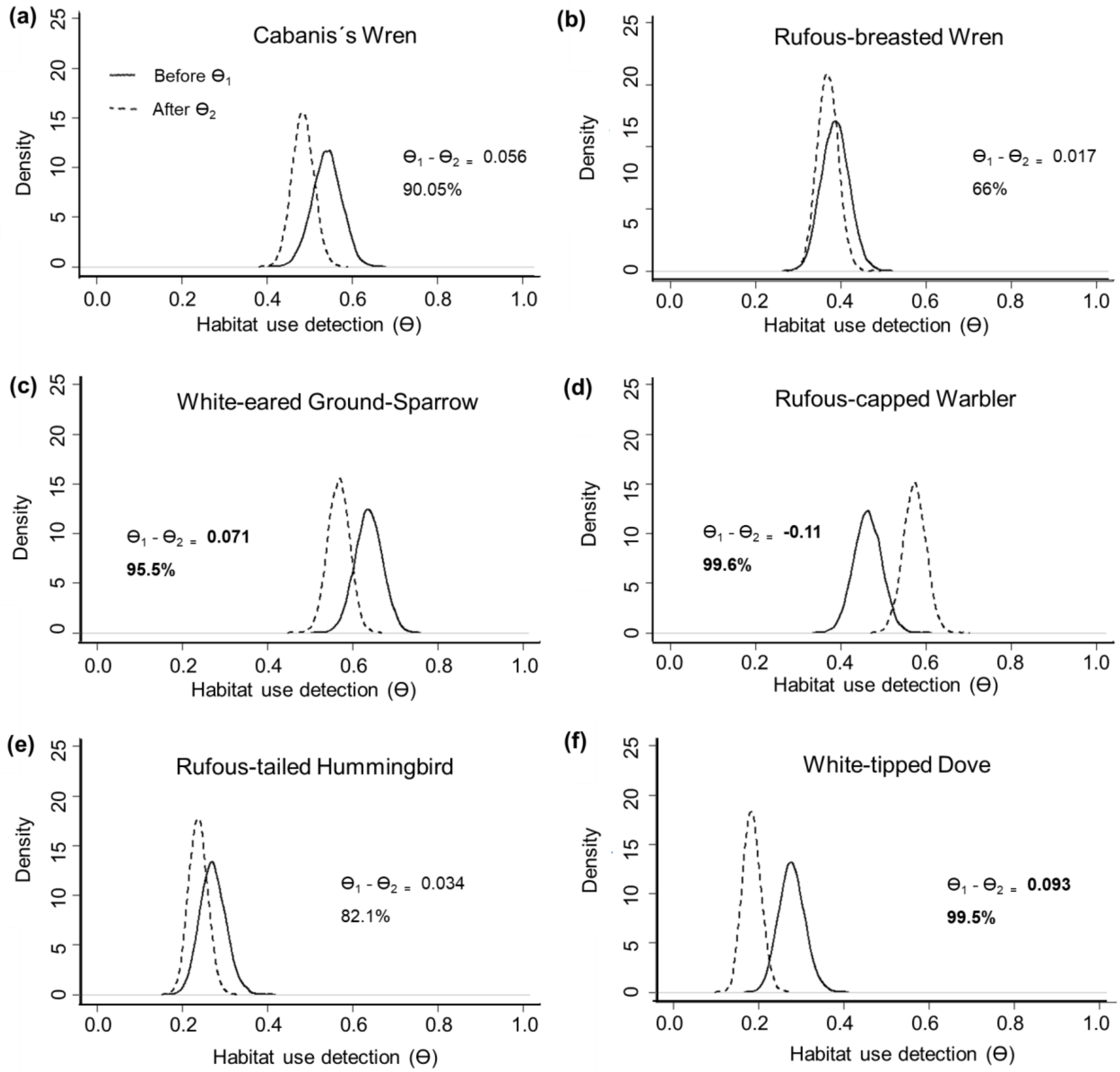

Figure 1. Relative frequencies of habitat use detection (Θ) during the pruning season for each one of the six species of birds. Θ1 correspond to the "before" values in a dotted line and Θ2 to the "after" values in a solid line. Change in Θ and probability percentages are shown for every specie.

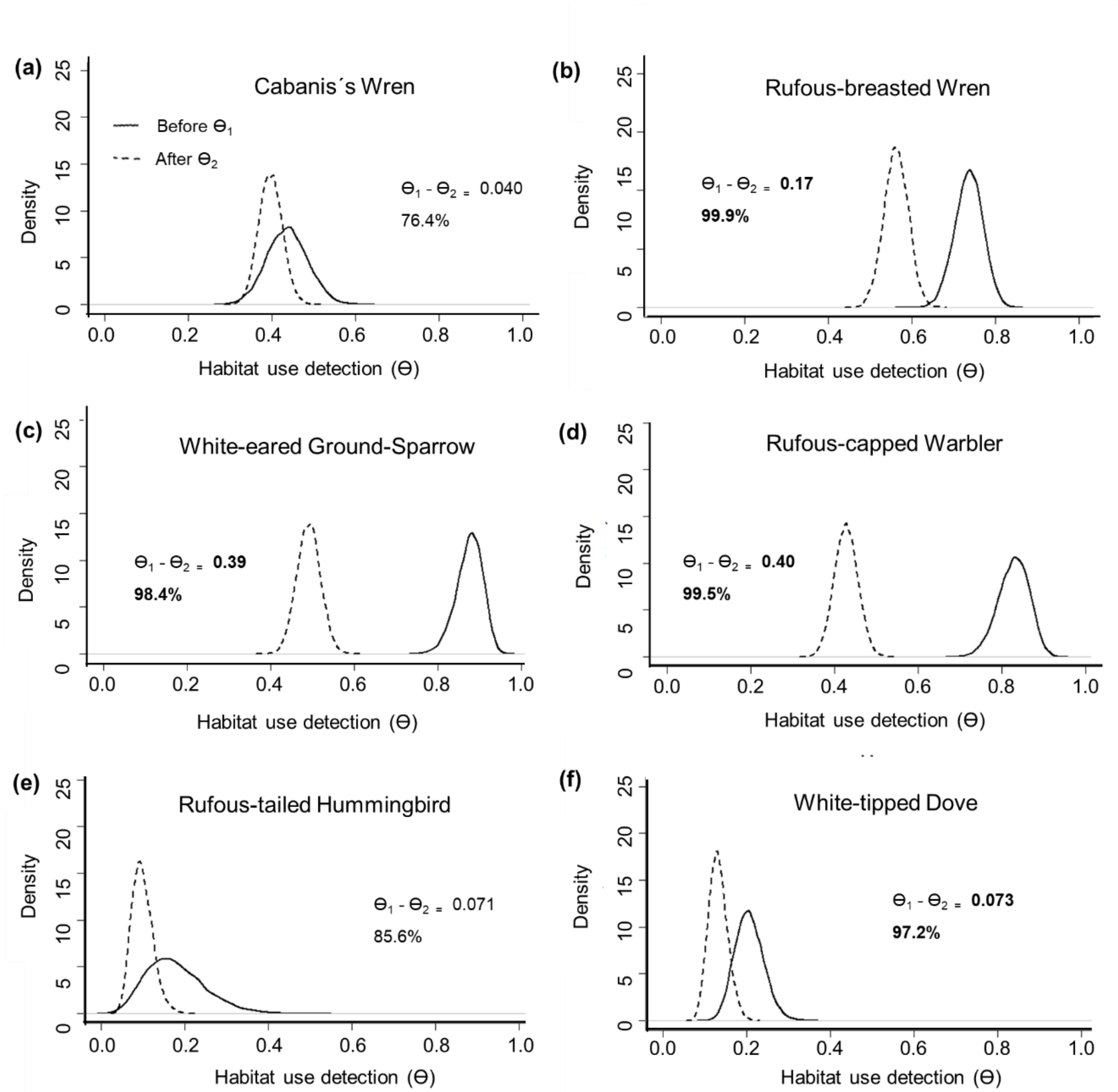

Figure 2. Relative frequencies of habitat use detection (Θ) during the application of agrochemicals season for each one of the six species of birds. Θ1 correspond to the "before" values in a dotted line and Θ2 to the "after" values in a solid line. Change in Θ and probability percentages are shown for every specie.

Capítulo 3. Bird community and perceptions of environmental well-being of coffee producing families.

Abstract

Sustainable agriculture must ensure producers and workers economic development and social welfare. To be able to measure this factors governments and NGO's have established several indexes to determine the level of human development and well-being. However, most indexes are not applicable at small local or household levels and fail to take into consideration the perception that people have about the quality of the environment. Wildlife diversity, and landscape features like canopy coverage, are variables that have shown positive impact on people's well-being and well-being perception in cities, suburbs, and natural areas. Here, we explore whether the perceptions of environmental well-being (Assessed by the Social Progress Index), of farmers that produce coffee, is related to previously calculated bird community values of coffee farms. Farmers' perception of environmental well-being was not directly related to bird community composition. The slight relationship observed could derive indirectly from components on the perception of well-being related to water quality. Indices that use surveys and aim to understand perceptions of well-being and sustainability should include questions about people's perceptions of the biodiversity around them. Environmental Well-being is an important variable to asses human development as is the level of income or access to health. The perception farmers have about biodiversity and wildlife surrounding them should be one more variable to assess it.

Key words: Social Progress Index, Biodiversity Progress Index, Social welfare, Community completeness, wildlife.

Sustainable agriculture aims to meet the population's demand for food, in a socially fair way conserving ecosystem services and maximizing the benefit for society (*Tilman et al*., 2002; Munier, 2005). This implies changes in behavior production, consumption, and perception of the environment patterns (Munier, 2005; de Snoo *et al*., 2013). The international market, consumers, and decision-makers make a pressure on farmers to switch to sustainable agriculture (Kross *et al*. 2018) and protect or improve the natural habitats in or around their farms (Kilian et al., 2006; Valkila, 2009). There are programs and certifications that request the protection of riparian forests and forest patches (e.g., Fair Trade, Rainforest Alliance, Shade Bird Friendly and AAA Sustainable Quality). These certifications work through market access, profit, or other incentives (Raynolds *et al*., 2007, ECOM, 2019), to, among other things, ensure that production is compatible with wildlife (Kross *et al*., 2018).

Sustainable agriculture must also ensure to producers and workers development and social welfare (Tilman *et al*., 2002; Munier, 2005; Kilian *et al*., 2006), this is partially reach with the observed increases in incomes, around 16–22%, of certified farms compared with not certified ones (Meenken,2020). However, in some studies, there is evidence that there is not increase in overall household assets (Oya et al., 2018). In the case of workers of certified coffee farms, wages do not vary in relation to their non-certified counterparts (Oya et al., 2018). But, comparisons between social welfare of the farmers and workers associated with food production, in certify and non-certify farms, are scares (Haight, 2007) and it becomes highly necessary to understand the benefits to work or have a certify farm.

Governments and NGO's have developed several ways to measure and determine the level of human development and well-being. However, the mainstream way to measure it relays on economic indicators, yet well-being cannot be calculated solely by per capita income in a family, nor by the gross domestic product of a country or region (Rosenberg, 1994; Mancero, 2001). To obtain good approximations of human development and well-being, indices need to account for access to vital needs and human rights (Salazar & Garcia, 2014). Historically the most common index used worldwide is the Human Development Index (HDI; Rosenberg, 1994; Salazar & Garcia, 2014), which measures variables of health education and income. A widely used index is the Better Life Index (BLI), which measures housing, income, education, and other 8 topics including environmental health and subjective well-being from a Gallup poll report (OCDE, 2020).

Recently the Social Progress Index (SPI) has been applied worldwide, because it measures economic variables but also aspects related to 17 of the UN sustainable development goals for 2030. It is designed to measure social progress in communities that do not have recent information for the diagnosis of social and environmental well-being (Stern et al., 2014), because it includes surveys and people's opinions. The SPI has, also, been adapted and applied for each local government in Costa Rica (Social Progress Imperative, 2020), and is a metric used by coffee companies (i.e., ECOM-Agro-industrial and NESPRESSO) to evaluate the social conditions of coffee farmers (E. Poncon, personal communication, October 20,2022),

Besides social well-being, there is also a void about the perception that farmers have about the quality of the environment and wildlife of their farms (Kross *et al.*, 2018). From the aforementioned indexes the SPI is the only one that has metrics about environmental well-being and that is scalable from community to country scale, even when updated information is not available (Social Progress Imperative, 2020). However, it does not include questions regarding biodiversity perceptions on their surveys (Social Progress Imperative, 2020). The abundance and diversity of animals, birds in particular, which people observe in their gardens, and the perception of biodiversity in general and landscape traits like canopy coverage, are variables that have shown positive impact on people's well-being and well-being perception in cities, suburbs, and natural areas (Hedblom & Gunnarsson, 2017; Schebella, et al., 2019; Ferraro et al 2020; Methorst et al., 2020).

In agricultural areas, positive or negative perceptions that different farmers have about birds in their farms depend of the effects those birds have on crop production (Kross *et al.*, 2018; Salermo et al., 2020). Here, we explore whether the perceptions of environmental well-being (Assessed by the Social Progress Index), of farmers that produce coffee, is related to previously calculated bird community values of coffee farms. This, as way to improve the metrics used to evaluate sustainability, through an external perspective, and contribute to the construction indicators of Environmental Well-being for social indexes and sustainability programs.

Methods

Study site

We conducted the study in the San Ramón region of Alajuela (10° 13' N, 84° 35' W), between 1,000 and 1,300 m a.s.l. and the basins of the Grande de San Ramón River and the Barranca River. Coffee farms are located throughout the region in the districts of Santiago, San Rafael, Alfaro, Piedades Norte, Piedades Sur, and Concepción. The land cover is a mix of crops (coffee, tomato, sugar cane, ornamental plants, smaller-scale subsistence crops of beans, corn, and oranges), grasslands, forest remnants, cattle lands, poultry, and pig farms. Wooded areas are remnants of riparian forest, protection zones for springs and creeks, or abandoned lands that regenerated naturally. The coffee farms that we studied have areas ranging from 1 to 7.5 ha. The farms are family owned and managed by several family members. All farms plant the *Coffea arabica* species.

Environmental Well-being

From September 2019 to June 2020 a Social Progress Index survey was conducted. The survey was addressed to coffee-producing families at San Ramón, and the answers were analyzed by the Latin American Center for Competitiveness and Sustainable Development of INCAE (See supplementary material). From that survey, we extracted the five questions that form the perception of Environmental Well-Being component of the SPI, and that provide information regarding. 1) The frequency of recycling at home. 2) The issues with garbage in the community. 3) The quality of the air in the community. 4) The quality of the air at home. 5) The quality of the water in the community. We excluded the question regarding recreational zones because it did not apply to the reality of the area of research. We constructed a numerical ordinal scale to grade each possible answer (See appendix I), and the numbers of the scale were added up to create a score per household. Finally, the score was transformed to a percentage to obtain the perceived Environmental Well-being value (EWB), where 100 means that the perception of Environmental Well-being for that household was the best, it could be, according to the indicators used (See supplementary material). The EWB was used as an ordinal approximation to a continuous variable for the analysis (Shebella, et al., 2019; Robitzsch, 2020).

From a total of 83 households surveyed, we selected 27 for the analysis, the ones that met three criteria. 1) Families that have their farm within the AAA Sustainable Quality™ program of NESPRESSO and ECOM Agro-industrial (ECOM, 2019). 2) Families that separate and manage their solid residues as suggested by the AAA Sustainable Quality™ program. 3) Families that live on the same farm they produce their coffee. This to ensure that the information used was from households exposed to the bird community that was assessed and that are complying with the sustainability program regulations

Bird Community Completeness

Community Completeness value expresses how many species from the species pool based on life zone and natural habitat, without human occurrence, are present locally and how many are absent (Pärtel et al., 2013; Lewis et al., 2016). It is a useful tool in evaluating biodiversity between sites with different or changing environmental traits and species richness (Noreika et al., 2020). We used the highest Community Completeness percentage value for each farm for the year 2019 (CC), a percentage of 100 means that maximum completeness is met (all the species that should be present, considering habitat type, are present withing a farm. The Community Completeness values we used for each farm are the results of the interactions of cumulative species (reported from eBird lists for the area), with each other, and 54 environmental variables (e.g., Canopy height, forest percentage, land use, altitude, precipitation; Davis et al., 2023), using Deep Hurdle Networks for Zero-Inflated Multi-Target Regression and deep learning for Multivariate Probit Models (Chen, et al. 2018; Kong, 2018).

Data Analysis

We used Pearson correlations and a correlation matrix (Friendly, 2002), using “corrgram” package in R statistical software, to evaluate the correlations between Environmental Well-being (EWB) and Community completeness (CC). We used a simple linear regression model to estimate the relationship between the Environmental Well-being scores (dependent variable) and Community completeness (independent). All assumptions for simple linear regression model where met. We added the district residency of the surveyed households as a covariate in a second model and used the F statistic to choose between two models. We used Spearman correlations to compare the relation between CC and each of the components of the EWB separately to explore the possibility of one of them having a stronger relation with Community Completeness Values.

We used Spearman correlations and a correlation matrix (Friendly, 2002), using “corrgram” package in R statistical software, to evaluate the correlations between each of the five Environmental Well-Being components of the SPI (recicling, garbage.problem, air.community, air.home, water.quality). This, to explore if the different components contributed independently to the EWB value. Additionally, compared the median of the highest and lowest valued EWB components (air.community and air.home) using a Mood´s median test (Conover, 1971).

Results

There is a slight (0.5) positive correlation between Environmental Well-being (EWB) and Community Completeness (CC) ($t = 2.8751$, $p = 0.01$; Fig.1). Community Completeness explained 24.8% of the variability of Environmental Well-Being ($\beta=1.23$, $r^2=0.24$, $F=8.27$, $p <0.01$). For every percentual point increased in Community Completeness of the farm, the Environmental Well-Being perception increased in 1.23 percentual points. However, the confidence intervals of that increase are between 0.35 and 2.11 percentual points, evidencing a lot of variation (Fig. 2). Separately, the component of the EWB that had the highest correlation with Community Completeness of the farms was water quality ($\rho=0.64$, $p = 0.001$) (Fig. 3).

Of the five components of the EWB score, the quality of the air at home (air.home) was the one farmers ranked the lowest, and quality of the air in the community (air.community) was the highest (Fig 4.). Medians between these two components, according to Mood´s median test were different ($Z=3.22$, $p = 0.001$) (Fig. 5). Spearman´s Correlation values between the components of the EWB value, showed there was not correlation over 0.5 between any of the components. (Fig.6). However, quality of the air in the community and quality of the air at home, have a slight positive correlation ($\rho=0.41$, $p=0.03$).

Discussion

Farmers perception of Environmental Well-being was not directly related to the Community Completeness values. The slight relation observed (Fig.2) could derived indirectly from components about the perception of Well-being related to water quality (Fig. 3), and the management of solid wastes in the farms and communities, which are factors that are proven to have effects in both birds (Liang, et al., 2020; Manning & Sullivan, 2021; Noreen & Sultan, 2021), and humans (Giusti, 2009; Schwarzenbach et al., 2010; Manisalidis et al., 2020). Those components were directly evaluated in the Social

Progress Index under the Environmental Well-being section (Social Progress Imperative, 2020).

Most farmers evaluated the quality of the air in their communities higher than the other components, and air quality in their homes at the lowest (Fig. 4). Nevertheless, both these components were not correlated to Community Completeness (Fig. 3). This seem to be contra-intuitive, however, when looking closely, this perception can be influenced by having a wood stove (which was observed in many households during the survey), but was not among the questions of the Social Progress Index survey. Also, there is bias of qualifying air withing human settlements of lower quality than agricultural fields, could also explain this difference (King, 2015).

In regards of the perception of birds withing coffee farms, extensive surveys are required to better asses it. Surveys should consider to differentiate between guilds (Insectivores, frugivores, carnivores, nectivores). As perception can vary if the farmers received either benefits or prejudice from wildlife, or even due to cultural beliefs (Echeverri et al., 2019; De Rito et al., 2022). Farmers associated with fruit production can have a less positive perception of fruit eating birds. Meanwhile farmers who produce crops not consumed by these animals, such as coffee, perceive them mostly as allies for pests' control (Kross *et al*., 2018).

We did not find a direct relationship between bird Community Completeness in the farms and perceptions of Environmental Well-being of the farmers, there is no component of the EWB value that could be used as proxy of the perception of birds and their benefits, because there was not component question that address biodiversity. However, it has been proven that birds are good indicators and bio-monitors of environmental quality (Jaspers, 2019; Morelli, 2021), and their presence can also increase good perceptions of Environmental quality and Well-being among people (Hedblom & Gunnarsson, 2017; Schebella, et al., 2019; Ferraro, et al., 2020; Methorst et al., 2020; Methorst et al., 2021).

Indexes that use surveys (e.g., SPI) and aim to get a grasp on perceptions of Well-being and sustainability should, include questions about people's perceptions of the biological diversity surrounding them, birds in particular, in order to have a more complete set of components to measure Well-being. On the other hand, for indexes where surveys or human perceptions are not to be used (e.g., HDI, BLI) then parameters that are remotely calculated, scalable and comparable between countries, like Community Completeness, can be used as indicators of biodiversity state (Pärtel et al., 2013; Noreika et al., 2020;) to supplement their environmental indicators (Mizobuchi, 2014; Biggeri & Mauro, 2018).

Conclusions

Environmental Well-being is an important variable to asses human development as is the level of income or access to health. The perception farmers have about biodiversity and wildlife surrounding them should be one more variable to assess environmental well-being. Yet, this perception is most of the time related to the benefits they perceived from it, and not every person is capable of detecting those benefits. Exploring the relationship between Well-being and biodiversity in general, or bird diversity in particular, is not a simple endeavor, and needs further concepts and schemes to be tested. At the same time, gaining understanding about the perception of people, in this case farmers, towards their surrounding conditions, including Environmental Well-being, can contribute to the monitoring and evaluation efforts both on the public and private sectors.

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Figures

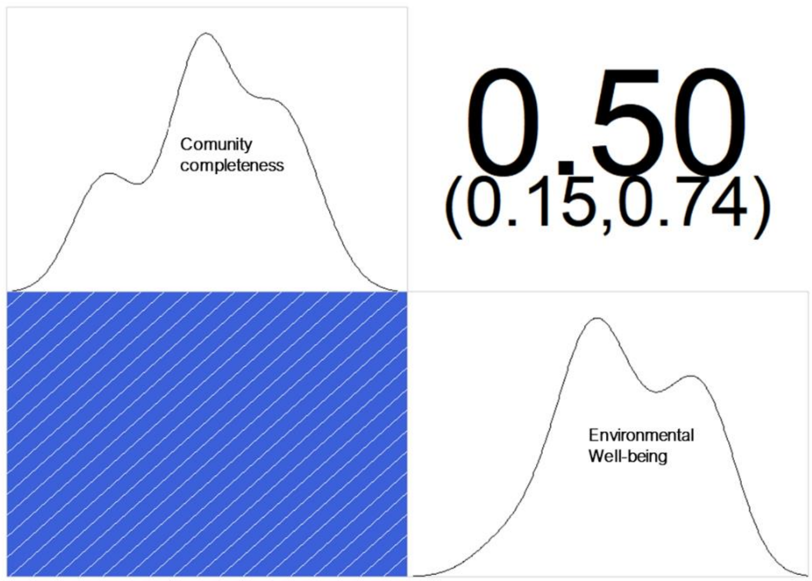

Figure 1. Correlation matrix based on Pearson correlation. Blue tones indicate positive correlation. The numbers between parenthesis are the Confidence intervals.

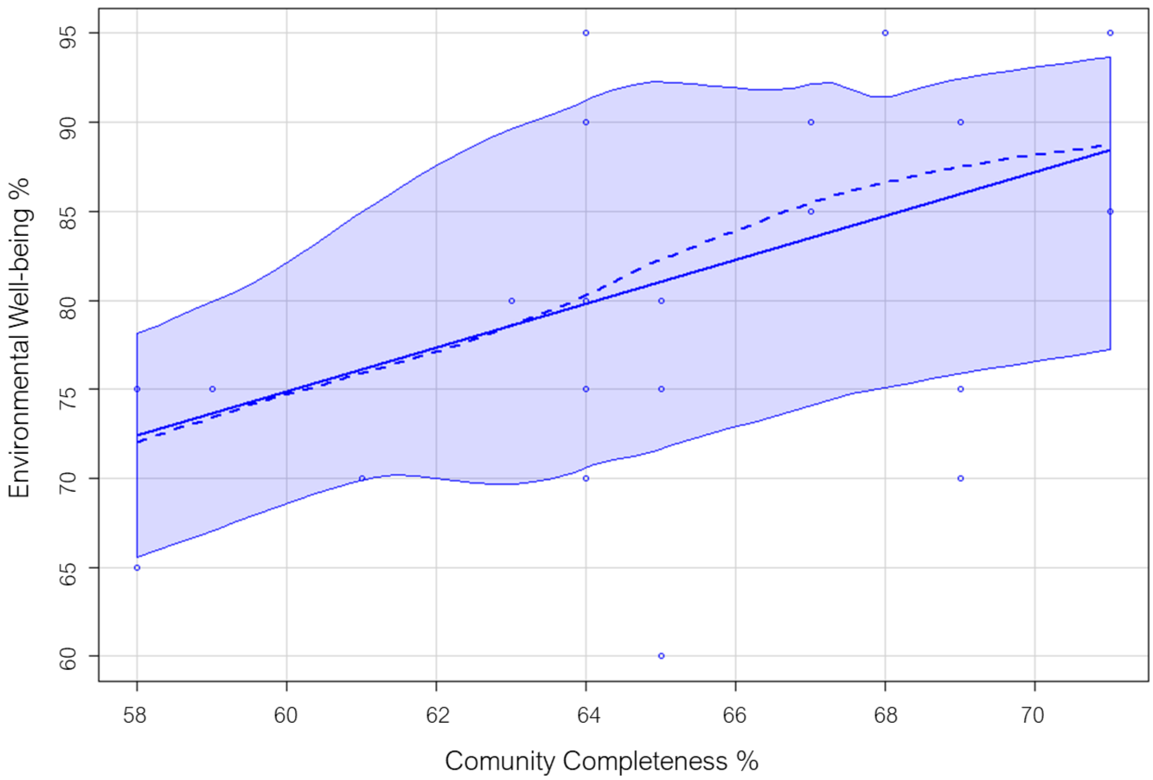

Figure 2. Scattrerplot of the simple linear regression model. The solid line correspond to the linear regression and the dotted line is the smoothing non-parametric representation, when both lines are close is an indication that the model could give a good description of the behavior to be expected.

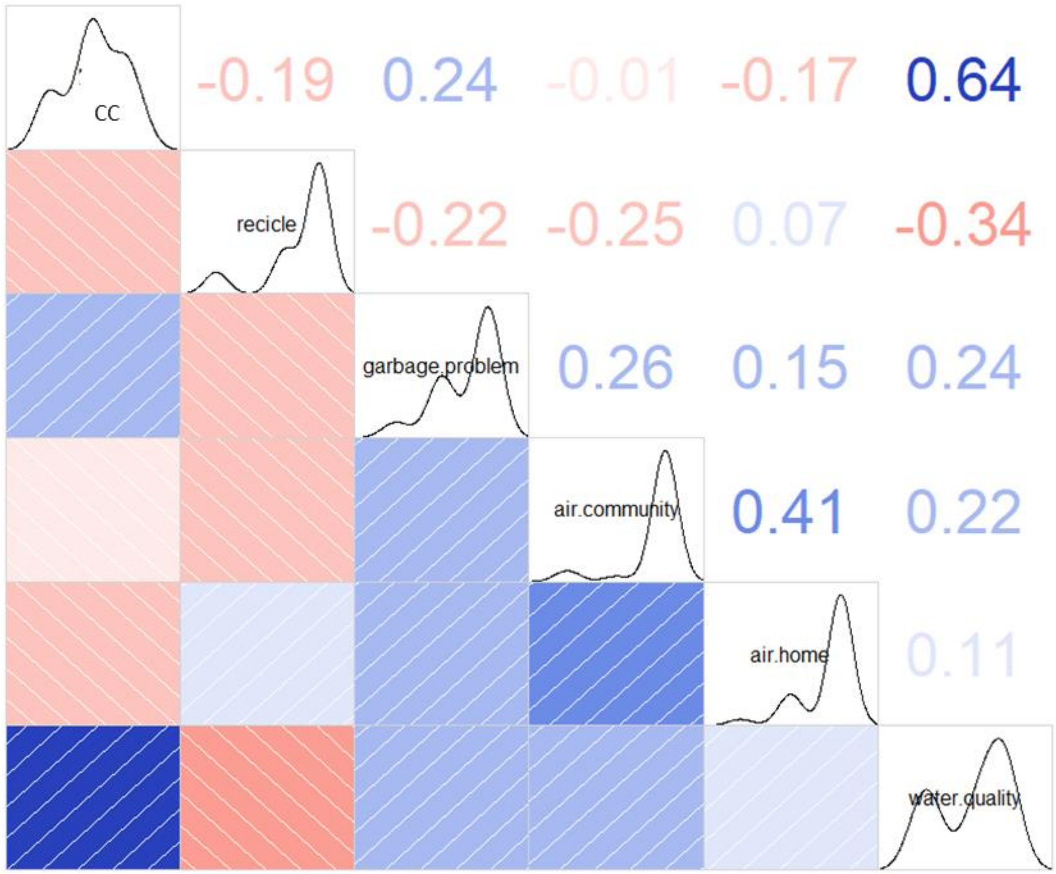

Figure 3. Correlation matrix based on Spearman correlation, comparing Community Completeness (CC) to the different components of the Environmental Well-Being value (EWB). Blue tones indicate positive correlation and red tones negative correlation.

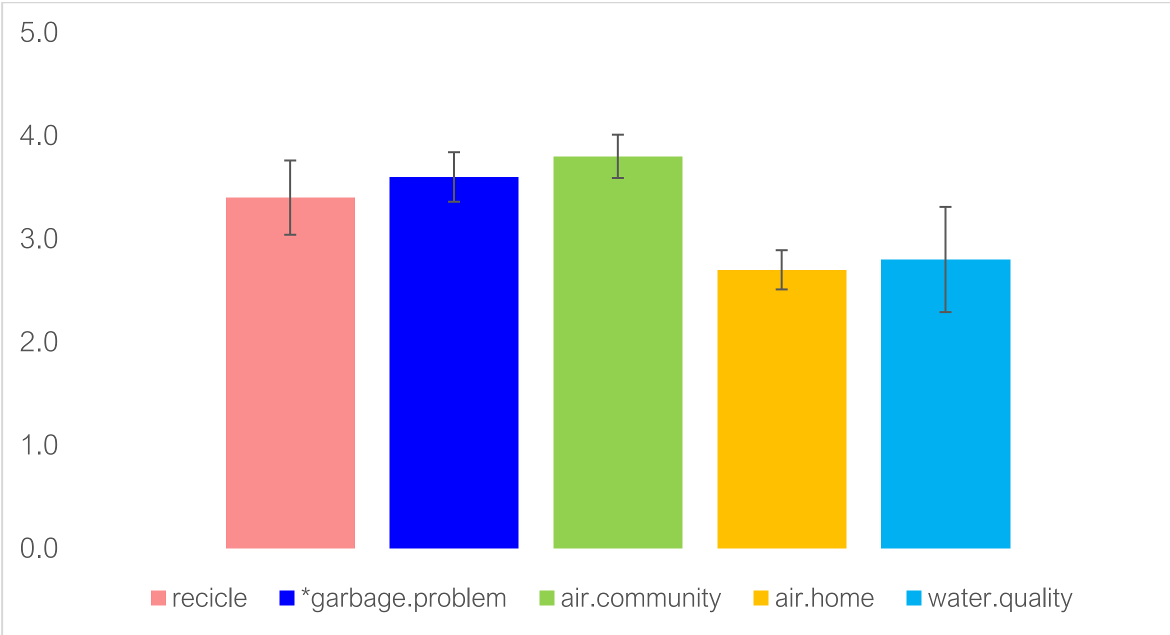

Figure 4. Categories that compose the Environmental Well-being score, and the average overall qualification given by the farmers. Whiskers correspond to confidence

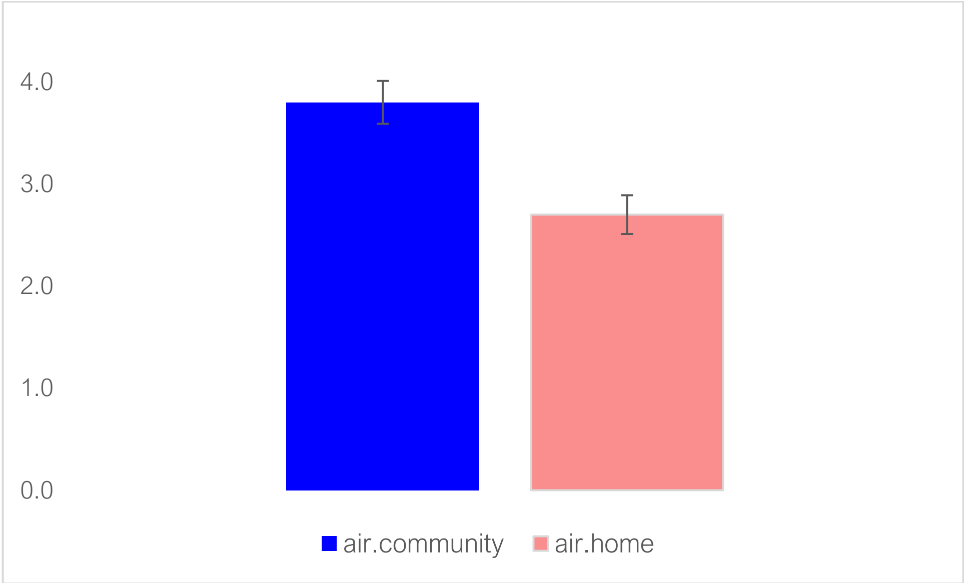

Figure 5. Air quality of the community and the home means. Whiskers correspond to confidence intervals.

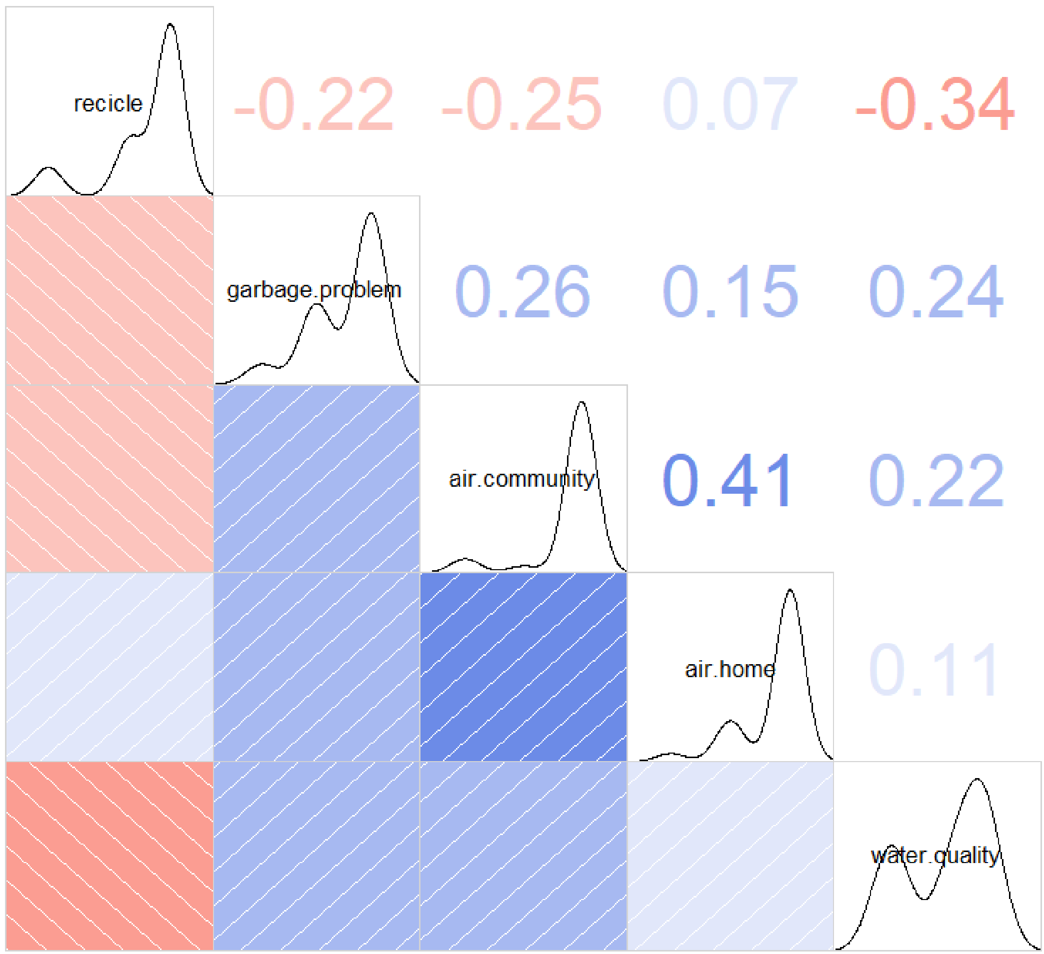

Figure 6. Correlation matrix based on Spearman correlation. Blue tones indicate positive correlation and red tones negative correlation.

Appendix 1.

Survey questions about perceptions of environmental quality and well-being in the SPI instrument of evaluation and the associated values to calculate the final score.

* 45. ¿En su casa se recicla o se separa la basura?

- Nunca — 1. Never
- Pocas veces — 2 Some times
- La mayoría de veces — 3 Most times
- Siempre — 4 Always
- No lo sé

Is there recicling or garbarge clasification at home?

recicling

* 46. Y para usted ¿cuán grave es la situación de la basura en su comunidad?

- Muy grave — 1
- Grave — 2
- Poco grave — 3
- Nada grave — 4
- No lo sé

How bad are garbage issues in your community?

garbage.problem

* 57. ¿Considera que en su comunidad el aire está limpio y libre de humo y olores?

- Nunca — 1
- Pocas veces — 2
- La mayoría de veces — 3
- Siempre — 4
- No lo sé

Do you think the air is cleand and free of smoke and bad odors in your community?

air.community

* 58. ¿Qué tan saludable cree usted que es el aire que se respira cerca de la vivienda donde usted habita?

- Nada saludable — 1
- Poco saludable — 2
- Bastante saludable — 3
- Muy saludable — 4
- No lo sé

How healthy is the air you breath near your home?

air.home

* 59. En su comunidad, existen ríos, lagos o mantos acuíferos?

- No
- Sí
- No lo sé

Are there any rivers, lakes and aquifers in your community?*

There are in all comunities at the study area *

* 60. ¿Considera usted que la calidad y limpieza de esas aguas es…?

- Nada adecuada — 1
- Poco adecuada — 2
- Bastante adecuada — 3
- Muy adecuadad — 4
- No aplica
- No lo sé

How clear and clean are those waters?

water.quality

Appendix 2.

Link to supplementary material and data base:
https://drive.google.com/drive/u/1/folders/19udEkA08cOwEruv8sk1bwnq-a4cyBMoF

CONCLUSIONES

Para lograr conservar la vida silvestre de manera efectiva, el sector agrícola debe de estar involucrado. Los programas y certificaciones de sostenibilidad son instrumentos que puede ser útiles para la conservación de algunas especies siempre y cuando estén diseñados con este fin y sus resultados sean medidos y evaluados. Los resultados de nuestra investigación en un paisaje cafetalero nos indican que la integración de árboles dentro de las parcelas de café e invertir en la reforestación de las riberas de los ríos y remanentes de bosque dentro de la finca y en las tierras vecinas es el mejor enfoque para aumentar la complejidad de la vegetación. Esto requeriría la participación de partes interesadas fuera del sector privado del café, como los miembros de la comunidad y los agricultores, quienes poseen terrenos no dedicados exclusivamente al café. Identificamos umbrales de cuatro atributos de la complejidad de la vegetación que pueden informar y evaluar las prácticas de manejo en las fincas cafetaleras, pero principalmente, agregamos un grano de evidencia sobre la importancia de los paisajes agrícolas productivos para los objetivos de conservación de la biodiversidad.

Por medio de la evaluación de otras prácticas de manejo en los cafetales, aplicación de agroquímicos y poda del café, concluimos que las seis especies que usamos como modelo mostraron diferentes respuestas a ambas prácticas dentro de los cafetales, siendo un buen ejemplo de la complejidad de las respuestas de las comunidades de aves a la producción de café y la necesidad de seguir analizando el efecto de esta práctica en otras especies y tipos de cafetales. Existe buena evidencia para inferir que los métodos de aplicación de agroquímicos y los métodos de poda afectaron la frecuencia relativa de detección del uso del hábitat. También probamos el uso de registradores autónomos para responder a estas preguntas y confirmamos que facilitan la recopilación de datos de manera continua. Finalmente, pudimos sugerir seis acciones básicas para disminuir los efectos negativos de estas prácticas mientras se avanza en la investigación sobre tasas de recuperación, técnicas de poda y técnicas y productos de aplicación química.

Finalmente, al explorar una de las herramientas utilizadas para medir el bienestar ambiental de los y las productores de café notamos que la percepción que tienen los agricultores sobre la biodiversidad y la vida silvestre que los rodea debería ser una variable más de esa evaluación. La percepción de bienestar ambiental es una variable importante para evaluar el desarrollo humano al igual que el nivel de ingresos o el acceso a la salud. Sin embargo, explorar la relación entre el Bienestar y la biodiversidad en general, o la diversidad de aves en particular, no es una tarea sencilla, y necesitan más conceptos y esquemas para ser probados. Al mismo tiempo, comprender la percepción de las personas, en este caso los agricultores, sobre las condiciones de su entorno, incluido el Bienestar Ambiental, puede contribuir a los esfuerzos de monitoreo y evaluación tanto en el sector público como en el privado.

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