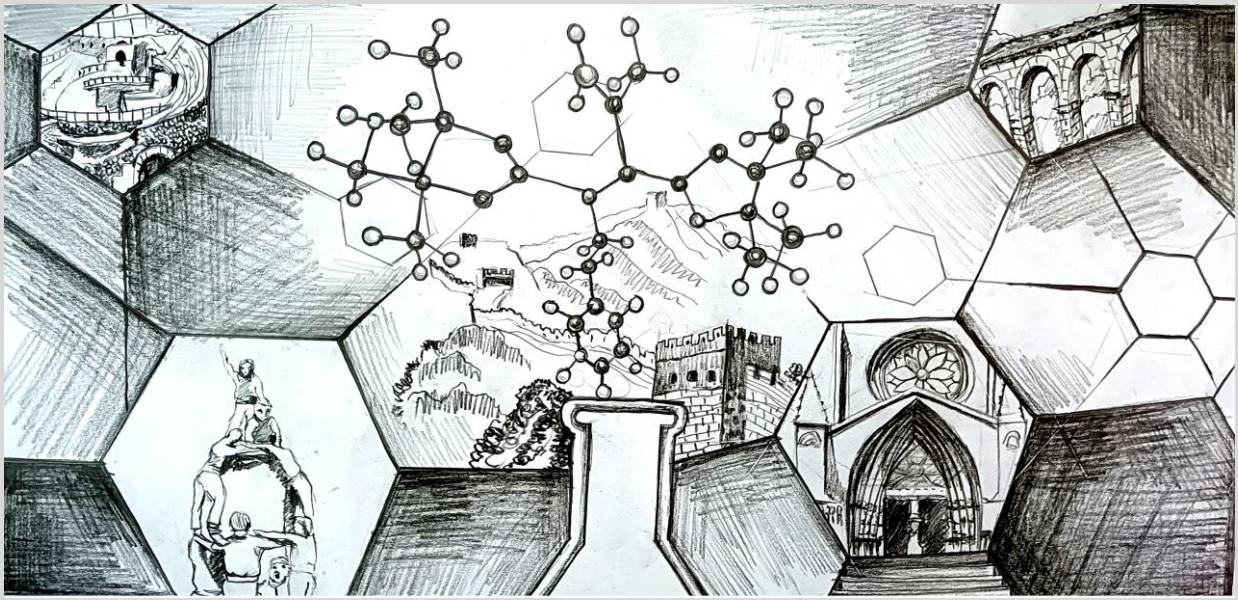
COPPER AND NICKEL PROMOTED TRANSFORMATIONS OF ALKYNE BASED CYCLIC CARBONATES

Kun Guo

UNIVERSITAT ROVIRA i VIRGILI

Copper and Nickel Promoted Transformations of Alkyne based Cyclic Carbonates

Kun Guo（郭坤）



DOCTORAL THESIS
2021

PhD Thesis

Copper and Nickel Promoted Transformations of Alkyne based Cyclic Carbonates

Kun Guo

Supervised by Prof. Dr. Arjan W. Kleij

Tarragona

December 2021

UNIVERSITAT ROVIRA i VIRGILI

ICIQ

UNIVERSITAT ROVIRA i VIRGILI

ICIQ

Prof. Dr. Arjan W. Kleij, Group Leader at the Institute of Chemical Research of Catalonia (ICIQ) and Research Professor at the Catalan Institution for Research and Advanced Studies (ICREA),

I STATE that the present Doctoral Thesis, entitled "**Copper and Nickel Promoted Transformations of Alkyne based Cyclic Carbonates**" presented by Kun Guo to receive the degree of Doctor, has been carried out under my supervision at the Institute of Chemical Research of Catalonia (ICIQ).

Tarragona, August 2021

Doctoral Thesis Supervisor

Prof. Dr. Arjan W. Kleij

Acknowledgements

Thanks to the support from many people, my doctoral study/time is coming to a final stage in a pleasant way. Except for the enormous gratitude to my parents, Prof. **Arjan Kleij** was the first person who came to my mind for my sincere appreciation. First of all, with his strong support, I managed to obtain a CSC Scholarship and a partially funded ICIQ PhD fellowship, which gave me the opportunity to start my PhD study and life in Spain. Thanks to his kindness and inclusion, I still received enough support from him when I made some bad judgements. I have learnt a lot from him, not only scientific knowledge, but also the development of personal characters. I am lucky to have had him as my supervisor because only a few professors would give their students the maximum freedom to investigate new reactions and manage their research projects. Even though my PhD study is a compilation of many failures and few successes, he taught me how to focus on the positive side and learn from the failed experiments. Now, I have more confidence and courage to continue my academic career with all the experience learnt from him.

Secondly, I would like to thank all the members from Kleij group, with whom I have shared all these years: Dr. **Bart Limburg**, Dr. **Debasish Ghorai**, Dr. **Arianna Brandolese**, **Alèria García**, **Sijing Xue**, **Chang Qiao**, **Nicola Zanda**, **Alba Villar**, **Jixiang Ni**, **Xuetong Li**, **Qian Zeng**, Dr. **Alexander Lücht**, Dr. **Rui Huang**, Dr. **Wusheng Guo**, **Cristina Maquilón**, **Àlex Cristòfol**, **Jianing Xie**, **José Enrique Gómez**, **Antonella Pizzolante**, Dr. **Jeroen Rintjema**, **Victor Laserna**, **Vatcharaporn Aomchad**, **Josefine Sprachmann**, **Christian Böhmer**, **Sarah-Elisabeth Dechent**, **Michela Marchese** and **Mariachiara Cozzolino**. In addition, I would like to express my appreciation to the people from the Research Support Area at ICIQ. **Xisco Caldentey** taught me how to use the HTE and gave me many supports when I optimized the reactions. **Israel Macho** and **Germán Gómez** helped me a lot with the NMR analyses. **Mariona Urtasun Plans** helped me with the use of polarimetry and CD experiments. **Meritxell Díaz Estirado** helped me to develop methods for the separation of racemic compounds including some very difficult ones. **Marta Giménez Pedrós** and **Cristina Rivero** helped me set up CO_2 related reactions.

Noemí Cabello helped me with most of the HRMS analyses. **Jordi Benet**, **Marta Martinez** and **Eduardo Carmelo Escudero** supported me with the X-ray analyses. **Xavier Asensio** made some special glassware that I used for some of the experimentation.

I would like to acknowledge the China Scholarship Council (CSC) for financing my doctoral study in the Kleij group at ICIQ.

Apart from people known from work, I would also like to express my gratitude to certain people I met in Spain. **Matheus Sampaio** used to play badminton and chess with me, and he always offered me help when I needed it. **Federico Dattila** always gave me good advice and great support, and apart from this he did many crazy things with me, for example hiking the 54.8 Km Reus-Prades-Reus or sleeping on the outside grass and waking up by the water spray. **Alèria García** is my best padel partner and she has given me the best gift, a set of hand-made chess pieces. **Francisco José Paredes**, **Xavier Camprubi** and **Clara Pagès Gallego**, thank you very much for playing chess and padel with me. **Elena Carretero** is my favorite padel partner. I have shared great memories with you all on padel matches: **Lluïsa Duat**, **Xenia Fuguet**, **Ana Isabel Soler**, **Jordi Pascual**, **Jordi Torrent**, **Hector Rizo**, **Lorenzo Avis**, **Joaquín Alberto Fernandez**, **Federico Cabre Vicens**, **Andrés Muñoz Díaz**, **David Velez Bernard**, **Hugo Vilar Weber**, **Sandi Badia**, **Antonio Paredes**, **María Dolores Varea**, **Àlex Cristofol**, **David Nieto**, **Pablo Mora Forte**, **Inmaculada Nevado**, **Fernando Burgueño**, **Pau Porta**, **Laura Solé**, **Jordi Solé**, **María José**, **Manuel Gomez Merino**, **Cristina Saenz de Pipaon**, **Rogelio Beltran**, **Carles Gracía Bofarull**…

Last but not least, thanks to the always good weather and the sunshine beach in Tarragona. Life could not have been better for me. I will cherish all these good memories.

Kun Guo, 2021

Curriculum Vitae

Kun Guo was born on August 15, **1991**, in Jiangsu, China. He studied applied chemistry at Soochow University in **2010** and obtained his BSc degree in **2014.** During his undergraduate studies, he worked on transition-metal-catalyzed alcohol C–H bond functionalization. In **2017**, he received his MSc degree in organic chemistry from the same university under the supervision of Prof. Yingsheng Zhao. During his MSc, he focused on Pd(II) catalyzed acetoxime-directed C–H functionalization of alcohols. In **2015**, he was awarded a Special Scholarship of Academic Excellence, the highest academic award of the Soochow University. In **2016**, he obtained a National Scholarship which is the highest honor for a postgraduate student. Moreover, he was nominated twice as the Honor of Excellent Postgraduate for two consecutive years. Thereafter, he obtained the predoctoral fellowship from Chinese Scholarship Council (CSC) that allowed him to start his PhD studies in **2017** in the group of Prof. Arjan W. Kleij at the Institute of Chemical research of Catalonia (ICIQ). The results described in this thesis have been communicated at several conferences including the XXXVII Bienal de la Real Sociedad Española de Química (Donostia-San Sebastián, **2019**), the 4th EuCheMS Conference on Green and Sustainable Chemistry (Tarragona, **2019**), the ICIQ-RedINTECAT School (Tarragona, **2019**) and the IV ICIQ PhD Day (Tarragona, **2020**).

List of publications

Publications related to this thesis:

(1) Copper-Mediated Dichotomic Borylation of Alkyne Carbonates: Stereoselective Access to (*E*)-1,2-Diborylated 1,3-Dienes versus Traceless Monoborylation Affording *α*-Hydroxyallenes

Guo, K.; Kleij, A. W. *Angew. Chem. Int. Ed.* **2021**, *60* (9), 4901-4906.

(2) Cu-Catalyzed Synthesis of Tetrasubstituted 2,3-Allenols through Decarboxylative Silylation of Alkyne-Substituted Cyclic Carbonates

Guo, K.; Kleij, A. W. *Org. Lett.* **2020**, *22* (10), 3942-3945.

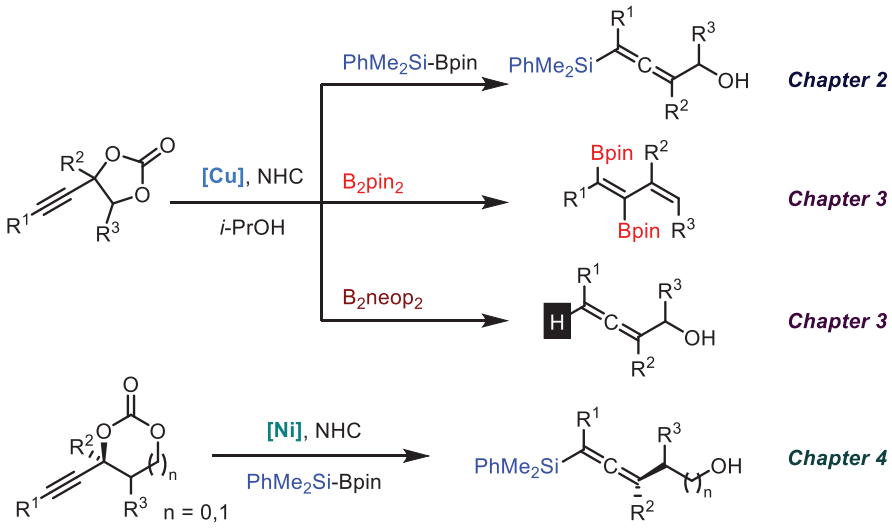
Contents

List of abbreviations

In this doctoral thesis, the commonly used abbreviations and acronyms in organic chemistry have been used following the recommendations from *The ACS Style Guide*, 3rd ed. which can be found at https://pubs.acs.org/doi/full/10.1021/acsguide.50308

Chapter 1

General Introduction



1.1 Inexpensive and abundant metal catalysis

One of these ambitions of organic chemists is to be able to synthesize organic compounds of importance, for instance in the context of medicinal applications or materials science. To achieve these goals, many approaches rely on transition metal (TM) catalysis, which has offered tangible solutions for challenging organic transformations (Figure 1).[1-3] Among the TMs, the platinum group metals (PGMs) have played a significant role in a wide range of industrial, medical, and electronic applications. The six PGMs are represented by ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) and platinum (Pt). They are also known as "noble metals" because of their catalytic properties and associated capacity to facilitate or control the rates of chemical reactions.

Contrary to their widespread applications, PGMs are rarely found in the earth crust. Their increasing demand and limited accessibility through mining has gradually created a non-sustainable situation. Replacing these noble metals with much more abundant ones (particularly in applications that use larger amounts of catalysts) would be desirable. Abundant metals give fewer problems related to supply fluctuations, they are cheaper and, in several cases, (Fe, Al) more environmentally benign. However, the reactivity of these rather inexpensive and abundant metals in organic transformation typically performed by TMs and/or PGMs needs to be understood, tamed, and developed to enable them as relevant alternatives. A lack of understanding of any new reactivity paradigm using abundant metal-based catalysts can and has led in certain cases to less selective catalysis and problems associated with the functional group compatibility. In other cases, rather complex (new) ligands must be used for efficient substrate conversion, and their cost should not exceed the price of any PGM. One must consider that in many important processes based on homogeneous catalysis, the cost of the metal is just a small portion of the overall expense.

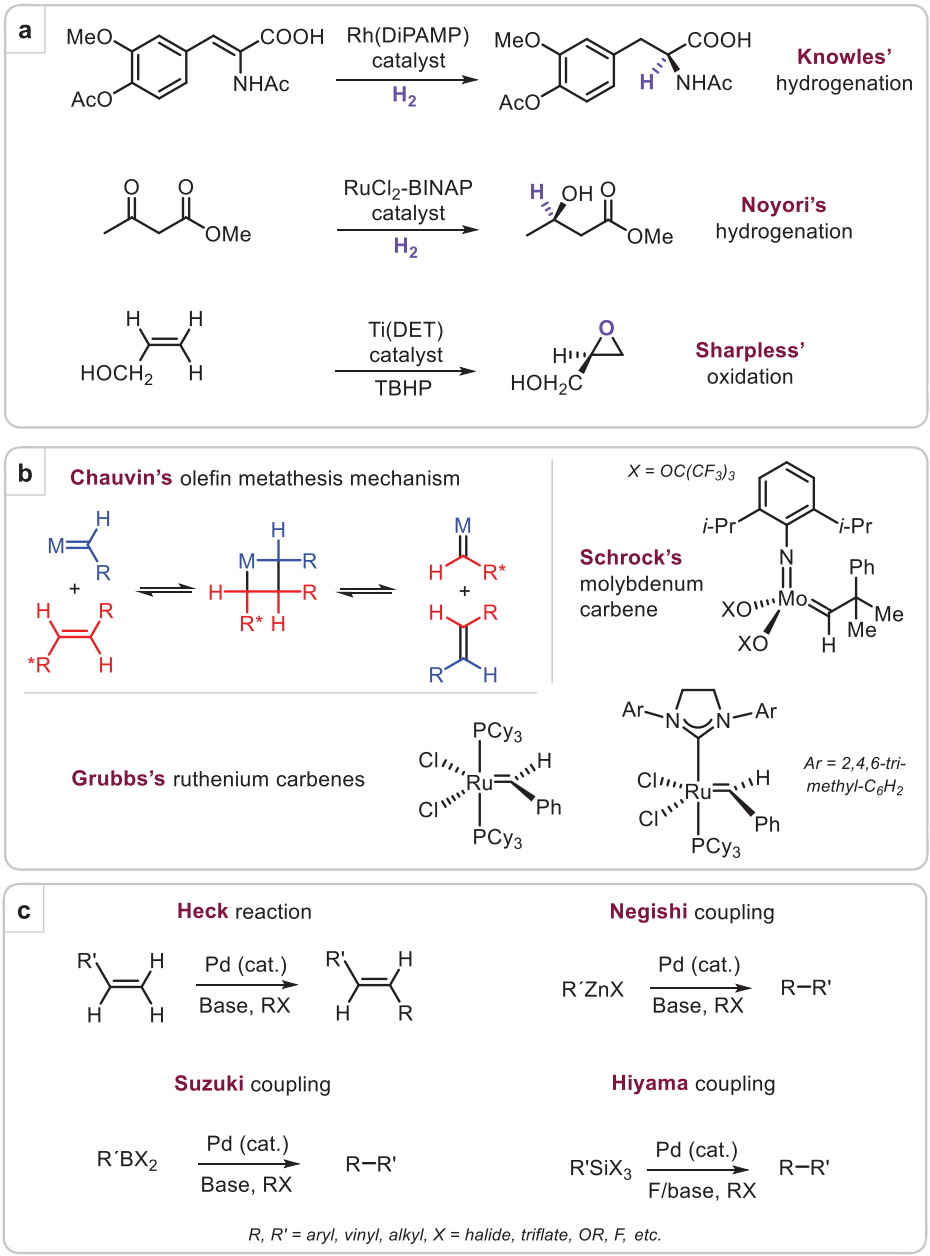


Figure 1. The importance of PGM/TM chemistry and catalysis: (a) 2001 Nobel Prize in chemistry, (b) 2005 Nobel Prize in chemistry; (c) 2010 Nobel Prize in chemistry, and Hiyama reaction.

Within this context, chemists are currently developing novel reactivity modes based on the use of homogeneous catalysts derived from inexpensive and abundant metals such that they can mimic the reactivity displayed by PGMs and/or provide new reactivity patterns. In the latter case it would present a way to expand on the currently known reactivity principles and prospectively provide a way to discover new transformations. Though in cases where a PGM represents just a fraction of the total cost, developing efficient catalysts from cheaper and more abundant metals is likely to produce significant savings. For example, palladium on a molar basis is approximately 3,000 times more expensive than copper, while ruthenium is 2,000 times more expensive than iron. Similarly, platinum is around 4,000 times more expensive than nickel and 10,000 times more expensive than iron.

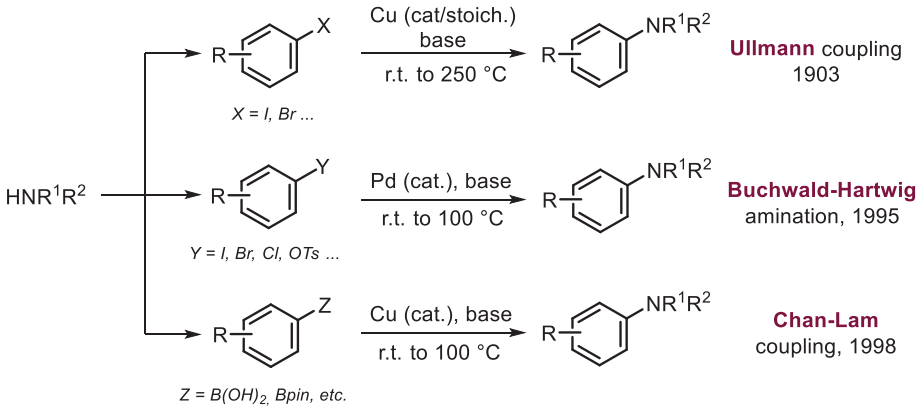


Figure 2. Important discoveries of metal catalyzed C_{Ar}–N coupling reactions for the synthesis of aromatic amines.

Pd-catalyzed cross couplings in organic synthesis (in which the metal is used to catalyze the formation of carbon-carbon bonds) are widely used to make complex materials, pharmaceutical ingredients, and biologically active compounds (Figure 1a). The Pd-catalyzed cross-coupling of amines and aryl (pseudo)halides, commonly known as the Buchwald−Hartwig amination, has become a fundamental transformation in synthetic chemistry and represents one of the most widely used conversions in the pharmaceutical

and agrochemical industries (Figure 2).[4-10] The loading of the metal in Pd-catalyzed carbon-carbon formation or amination reactions can be as low as 10 parts per million in some situations thereby reducing the cost significantly. Another way to reduce the overall cost of the above-mentioned processes is to replace Pd by other economically more benign alternatives.

About a 100 years ago, Ullmann reported the Cu-promoted conversion of aryl halides to aryl ethers, aryl thioethers, aryl nitriles and aryl amines. These conversions were later named Ullmann-type reactions.[11] These Ullmann-type conversions, especially aminations, are comparable to Buchwald–Hartwig aminations but traditionally the former transformations require higher reaction temperatures and stoichiometric amounts of Cu. A major breakthrough in C–heteroatom bond formations was the development of Cu(II)-promoted *O*– and *N*-arylation with boronic acids independently reported by Chan and Lam, also known as Chan-Lam coupling.[12] By using a suitable amino acid as ligand, Ma et al. discovered a new Cu catalyst that enabled Ullmann-type aryl aminations at temperatures below 100 degrees.[13]

In addition to the huge economic benefit by replacing a rare and expensive metal with a prevalent and cheap metal, cheap metals are often more environmentally benign. In the case of expensive metals, it is necessary to consider (1) recycling methods to reuse the catalyst and/or metal components, and (2) to remove trace levels of residual catalyst in the final products to accommodate their potential use in processes that focus on the synthesis of pharmaceutical ingredients and medicine. For the cheaper metals, loss of metal can be more easily tolerated in an industrial process from an economic point of view. Beside their natural abundance, these metals are often present in the daily food we consume. For example, 1 L of cow milk contains about 50 μg of copper and 500 μg of iron. In the case of noble metals, there is still much controversy about their toxicity in relation to human health and the environment. As noble metals are widely used as catalysts in fine-chemical and synthesis with a pharmaceutical/medicinal objective, they are more likely to pollute the environment.[14]

1.2 Copper-catalyzed reactions with propargylic surrogates: carbonates, carbamates, benzoxazinanones, indoloxazolidones and lactones.

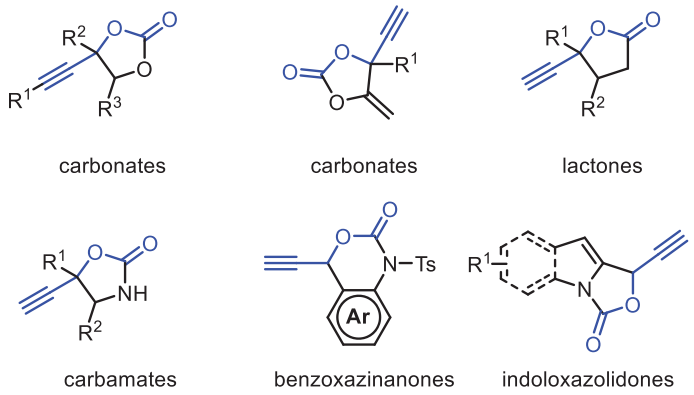
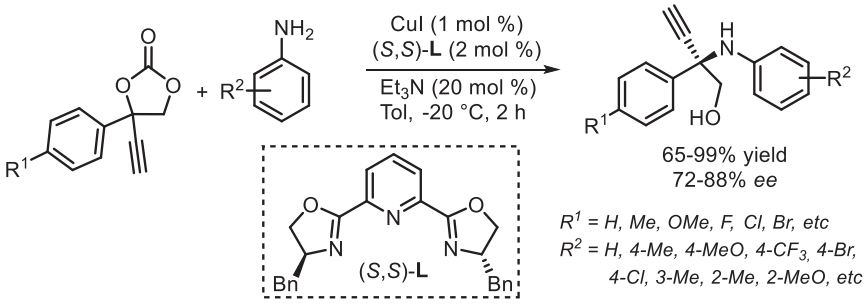


Figure 3. Propargylic surrogates derived from cyclic carbonates and related heterocycles.

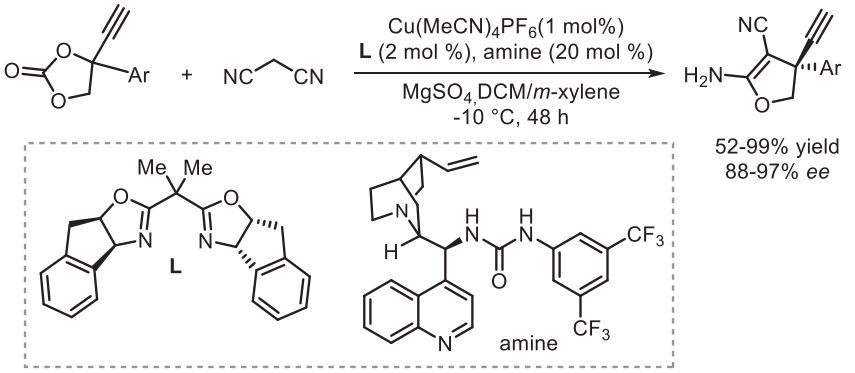
The development of the transition-metal-catalyzed propargylic substitution or S_N2'-type reactions of propargylic cyclic carbonates and similar heterocycles (Figure 3) has become an active field of research in organic synthesis.[15] Copper catalysts are well-known for promoting the asymmetric propargylic substitution of the terminal alkyne-substituted cyclic carbonates via copper−allenylidene intermediates.[16-17] However, copper-catalyzed S_N2'-type reactions of internal alkyne-substituted cyclic carbonates and similar heterocycles only are rare, even though stoichiometric versions of Cu-[18–19] and Pd-based processes[20-23] have been known for more than two decades.

In 2018, Zhang and co-workers described the Cu-catalyzed enantioselective synthesis of tetrasubstituted *β*-amino alcohols starting from propargylic carbonates and aryl amines. The reaction was performed at −20 °C in toluene and in the presence of triethylamine and (*S*,*S*)-L as ligand (Scheme 1).[24] Using this procedure, novel *β*-amino-*β*-ethynyl alcohols were obtained in 65–99% yields and with 72–88% *ee*. When reacting propargyl carbonates bearing naphthyl or heterocyclic groups under the optimal conditions, the efficacy of the method was maintained, giving the desired products in 93% (78% *ee*) and 98% (54% *ee*)

yield, respectively. A single example of an aliphatic amine substrate was tested (*t*-butylamine) and the target *β*-amino alcohol was produced in 75% yield and 64% *ee*.



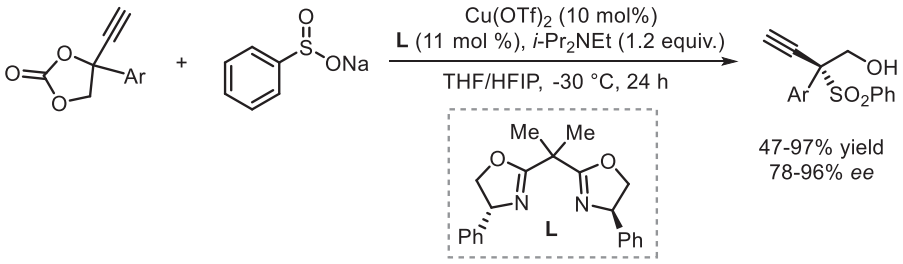
Scheme 1. The copper-catalyzed enantioselective synthesis of highly substituted *β*-amino alcohols.



Scheme 2. Copper/organo cooperatively catalyzed enantioselective [3+2] cycloaddition reactions of alkynyl carbonates with malononitrile.

In 2018, Song and co-workers communicated a [3+2] decarboxylative cycloaddition reaction between alkynyl carbonates and malononitrile through cooperative Cu/amine catalysis for the enantioselective construction of 2-amino-3-cyano-dihydrofuran derivatives. These copper-catalyzed cycloaddition reactions occur through the intermediacy of a copper−allenylidene intermediate (Scheme 2).[25] The reactions between alkynyl carbonates and malononitrile were performed in DCM/*m*-xylene at −20 ºC, and

produced the corresponding polysubstituted dihydrofurans in 50–99% yield and with 88–97% *ee*. This method could also be extended to alkyl-substituted alkynyl carbonates and ethynyl oxazolidinone, affording the desired products in 44% (77% *ee*) and 45% (74% *ee*) yield, respectively. Moreover, the reaction was compatible with a variety of functionalities and was amenable to scale up.

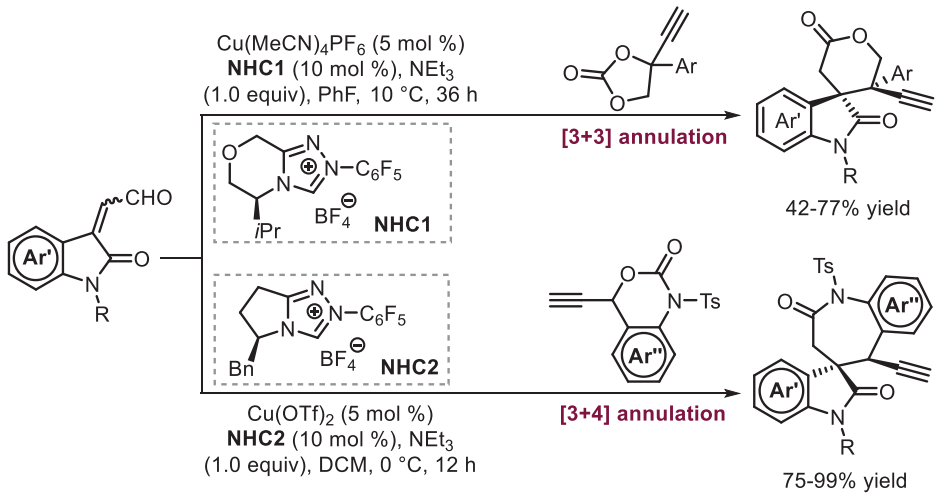


Scheme 3. Cu-catalyzed enantioselective construction of tertiary propargylic sulfones.

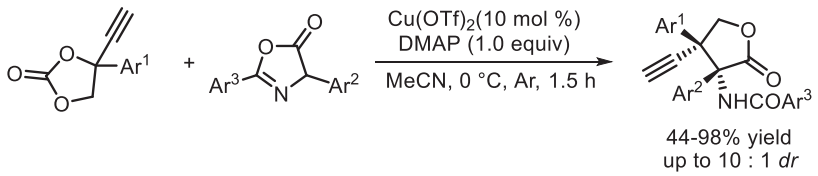
In 2019, Kleij and co-workers disclosed a versatile Cu-catalyzed enantioselective sulfonylation of propargylic carbonates using sodium sulfinates which allowed the construction of propargylic sulfones featuring elusive quaternary stereocenters (Scheme 3).[26] The reactions between racemic alkynyl cyclic carbonates and sodium aryl and alkyl sulfinates were conducted in a mixture of THF/HFIP at −30 °C in the presence of $Cu(OTf)_2$, bis(oxazoline) ligand **L** and *i*-Pr_2NEt. This method is characterized by high enantiomeric ratios and appreciable scope with respect to the reaction partners.

In the same year, Gong and co-workers reported the highly enantioselective [3+3] and [3+4] annulations of isatin-derived enals and alkynyl carbonates or benzoxazinanones by dual NHC/Cu catalysis leading to various spiro-oxindole derivatives with high structural diversity (Scheme 4).[27-28] They carried out the process with $Cu(MeCN)_4PF_6$, **NHC1** and NEt_3 in fluorobenzene (PhF) at 10 °C. They expanded the protocol to asymmetric [3+4] annulations of isatin-derived enals with propargylic benzoxazinanones for the preparation of chiral spiro-benzaepinones, with the combination of $Cu(OTf)_2$ and **NHC2** in DCM being best binary catalyst system. The isatin-derived homo-enolate species showed high

reactivity toward the transient Cu-allenylidene intermediates. The NHC played a double role serving as an organocatalyst to generate the enals, and as a ligand for Cu to tune the metal catalysis.



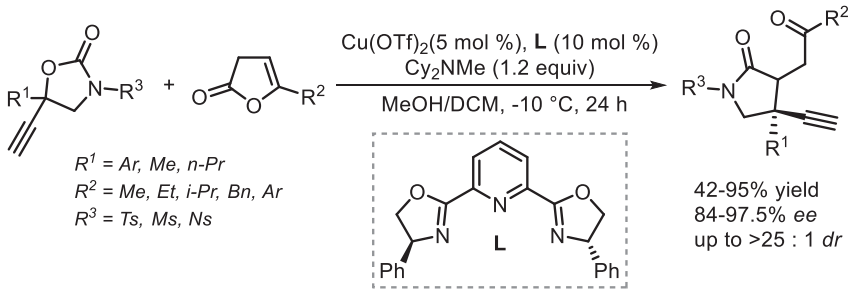
Scheme 4. NHC/Cu dual catalysis for the asymmetric of spiro-oxindoles.



Scheme 5. Cu-catalyzed decarboxylative [3+2] annulation of alkynyl carbonates with azlactones.

In 2021, Yuan and co-workers developed an efficient decarboxylative [3+2] annulation reaction between alkynyl carbonates and azlactones with a simple Cu salt as pre-catalyst (Scheme 5).[29] Their protocol included the use of $Cu(OTf)_2$ and DMAP in DCM at 0 °C giving access to a diverse library of γ-butyrolactones bearing two vicinal quaternary carbon centers. Noteworthy, the utilization of an alkynyl-substituted oxazolidinone substrate also gave productive catalysis to give the desired product in 82% yield and with 87:13 *dr*.

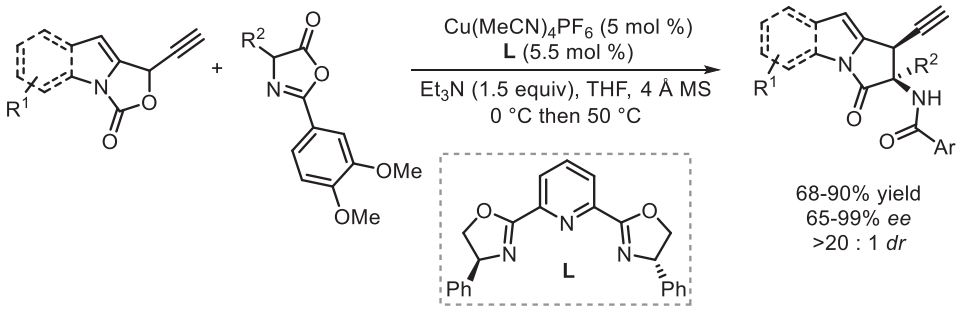
However, a 4-(phenylethynyl)-substituted carbonate was not converted under the standard conditions. Preliminary trials on enantioselective variants in the presence of a chiral Pybox ligand afforded the respective product in 71% *ee*.



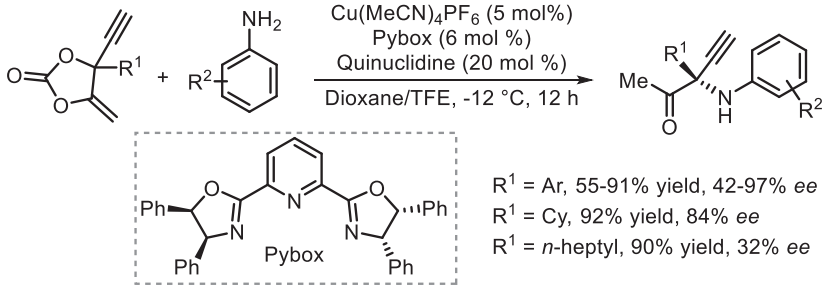
Scheme 6. Diastereo- and enantioselective Cu-catalyzed decarboxylative ring-opening [3+2] annulation of tertiary alkynyl cyclic carbamates.

Hu and co-workers reported in 2019 a Cu-catalyzed regio-, diastereo-, and enantioselective decarboxylative ring-opening [3+2] annulation of tertiary alkynyl carbamates and γ-substituted butenolides creating a way to access optically active pyrrolidinones (Scheme 6).[30] In a 2:1 solvent mixture of MeOH and DCM, the chiral pyrrolidinones were efficiently produced in the presence of a diphenyl-substituted Pybox ligand. Of particular note is that these reactions proceed through a rarely exploited α-attack on the γ-butenolides due to steric hindrance between the copper−allenylidene complex and dienolate intermediate.

Further to the previous examples, Deng and co-workers reported a Cu-catalyzed asymmetric propargylic [3+2] annulation of alkynyl indoloxazolidones and azlactones to give highly functional pyrrolo[1,2-a]indole products bearing contiguous quaternary and tertiary stereogenic centers (Scheme 7).[31] By controlling the temperature and reaction time, highly functional pyrrolo[1,2-a]indole scaffolds were prepared with excellent diastereo- and enantioselectivities in the presence of $Cu(MeCN)_4PF_6$ and a diphenyl-substituted Pybox ligand.



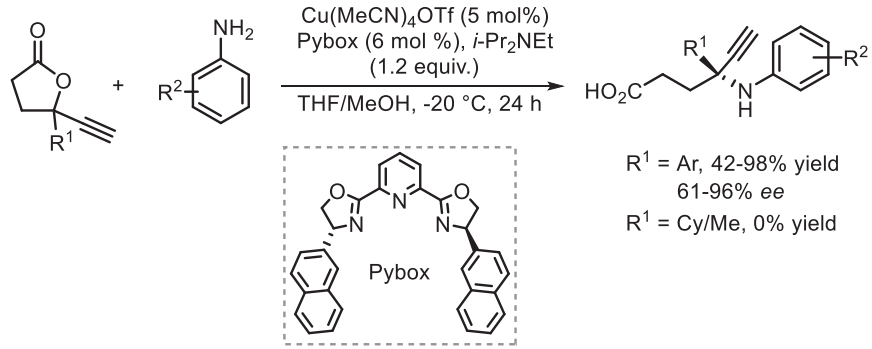
Scheme 7. Catalytic asymmetric [3+2] annulation reactions via indolyl Cu−allenylidene intermediates.



Scheme 8. Cu-catalyzed propargylic amination approach toward chiral acyclic α-quaternary α-amino ketones.

The Guo group developed a propargylic amination that enables rapid access to chiral acyclic *α*-quaternary *α*-amino ketones (Scheme 8).[32] They rationally designed an alkynyl functionalized cyclic carbonate as a propargylic surrogate, which after appropriate activation and decarboxylation generates a Cu-bonded enolate type zwitterionic intermediate. The reaction of these carbonates and anilines are catalyzed by $Cu(ACN)_4PF_6$ in the presence of a Pybox ligand and using quinuclidine as the base. Their protocol featured wide functional group diversity and high asymmetric induction. One example, with the presence of an iodine atom at the *α*-position of the substrate, could also be transferred into the desired amino ketone in 76% yield and with 87% *ee*. The authors proposed that the unique planar enolate geometry and zwitterionic structure of the

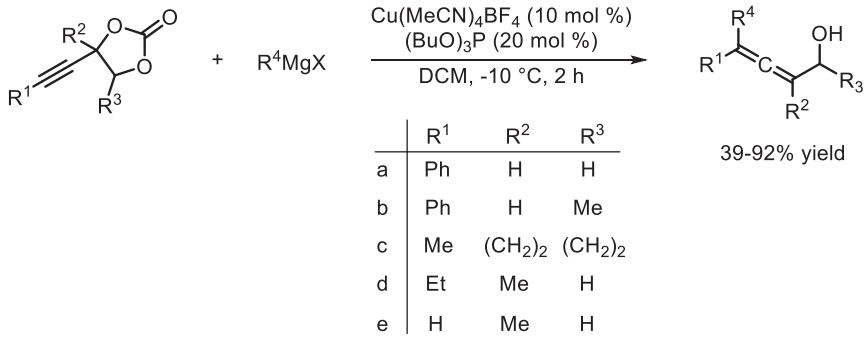
intermediate enables the high efficiency of these reactions leading towards the target *α*-amino ketones with high enantio-control.



Scheme 9. Copper-catalyzed ring opening of non-strained lactones with amine nucleophiles.

In 2019, our group reported the first asymmetric synthesis of *γ*,*γ*-disubstituted *γ*-amino acids through a Cu-catalyzed ring opening of non-strained lactones in the presence of amines (Scheme 9).[33] The reaction with the lactone and aniline at -20 °C in a mixture of THF and MeOH was catalyzed by 5 mol % of $Cu(MeCN)_4OTf$ in the presence of a chiral Pybox ligand. The catalytic system proved to be efficient for the conversion of lactones with both electron-withdrawing and -donating groups present in the aryl substituents (R^1) delivering the amino acids in good yields and high enantio-induction. However, lactone substrates bearing either a cyclohexyl or methyl group proved to be unproductive, which suggested a significant electronic bias within this catalytic process. The use of aryl amines bearing electron-donating groups afforded the *γ*-amino acids in both high yields and enantioselectivity, whereas aryl amines equipped with strongly electron-withdrawing substituents gave inferior results even when the reactions were performed at higher temperature. The reactions with benzyl amine, morpholine and propargylic amine at -20 °C for 24 hours displayed low conversion (<5%), while reasonable reactivity was observed at 0 °C though at the expense of the enantio-discrimination. The asymmetric induction was

suggested to arise by a well-established bimetallic model in which the amine attack on the *Si*-face of the copper-allenylidene intermediate is favored.



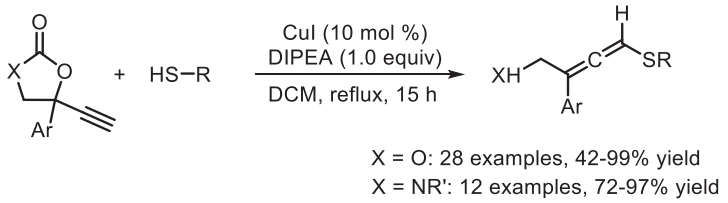
	R^1	R^2	R^3
a	Ph	H	H
b	Ph	H	Me
c	Me	$(CH_2)_2$	$(CH_2)_2$
d	Et	Me	H
e	H	Me	H

Scheme 10. Copper-catalyzed S_N2' substitution of alkynyl substituted dioxolanones.

Krause and co-workers discovered that efficient S_N2' substitution of alkynyl cyclic carbonates could be achieved with a copper(I)/$P(OBu)_3$ (pre)catalyst using Grignard reagents as nucleophiles (Scheme 10) delivering α-hydroxyallenes as products.[34] A range of primary and secondary *α*-hydroxyallenes bearing various functional groups were synthesized in good to excellent yields following this protocol. However, the use of a terminal alkyn-substituted cyclic carbonate resulted in relatively low yield of the α-hydroxyallene (39%–62%) due to competing deprotonation of the terminal alkyne-H in the presence of the Grignard reagent. Regarding the scope of Grignard reagents, both aliphatic (Et, *i*-Pr, *t*-Bu) and aromatic(Ph) nucleophiles were successfully utilized in this manifold. The process was also demonstrated to have potential towards the synthesis of enantiomerically enriched allenes.

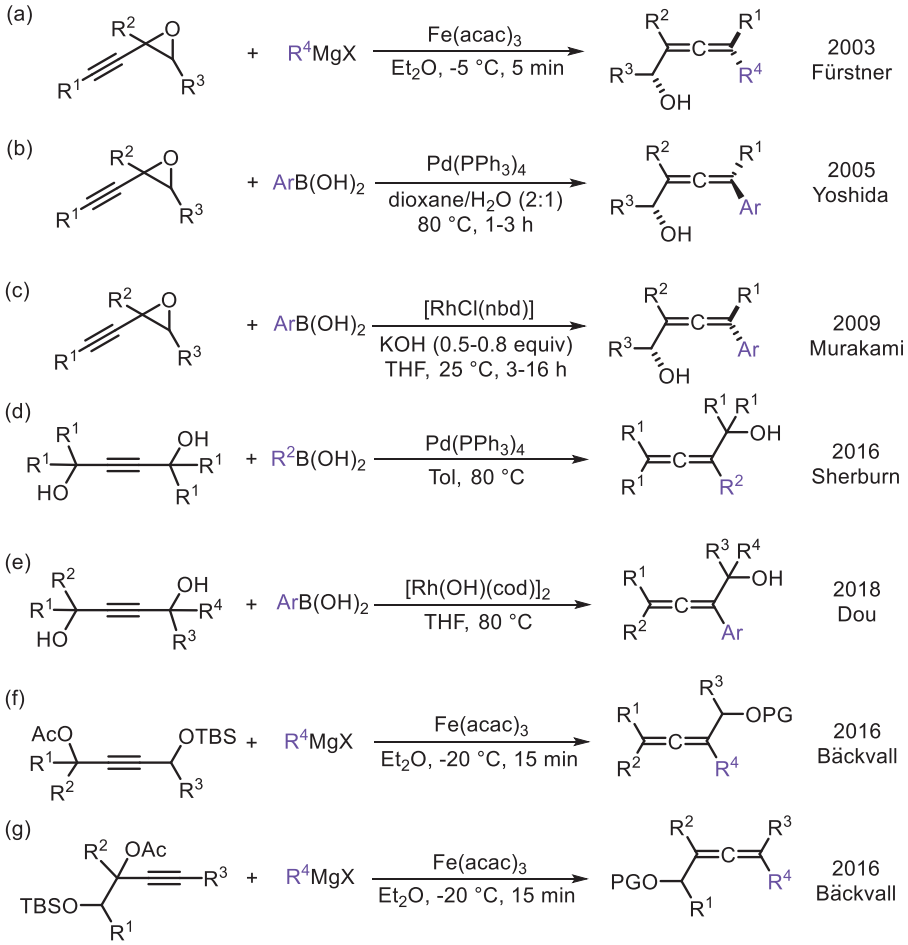
Finally, Yuan and co-workers developed a CuI-catalyzed decarboxylative thiolation of terminal alkyne-substituted cyclic carbonates/carbamates to access allenes (Scheme 11).[35] In the presence of 10 mol % of CuI and DIPEA, alkynyl cyclic carbonates and carbamates were converted into hydroxymethyl- and aminomethyl-containing allenyl thioethers, respectively, by reacting with phenylmethane thiols. When non-terminal alkyne-

substituted cyclic carbonate substrates (Ph or cyclopropyl terminated) were tested, no reaction was observed. Based on several control experiments, they proposed that the terminal alkyne moiety in the cyclic carbonate substrates is vital for the formation of a requisite Cu-allenylidene intermediate.



Scheme 11. CuI catalyzed decarboxylative thiolation of propargylic cyclic carbonates/carbamates.

1.3 Synthesis of multi-substituted allenols



Scheme 12. Synthesis of substituted *α*-allenols via S_N2'-type reactions with carbon-based nucleophiles.

Allenes do not only have certain types of reactivities and properties similar to alkenes and alkynes, but also they represent versatile building blocks for advanced organic synthesis building on their axially chiral backbones.[36-45] They can be considered as electrophiles and nucleophiles depending on the reaction conditions, and they can undergo

cycloaddition reactions and thermal or radical rearrangements.[46-55] Allenols, constituting an allene moiety and a hydroxyl functional group through diverse connectivities have become important building blocks for the synthesis of various bioactive structures and natural products.[56] On the one hand, allenols can be viewed as π-activated alcohols showing versatile reactivity towards elimination, substitution and rearrangement reactions. On the other hand, they can be viewed as allenes bearing additional electron pairs, which promote intramolecular cyclization or provide an alternative metal-coordination site. This part of the general introduction is focused on the synthesis of allenols from alkynyl epoxides and alkyne diols via transition metal catalysis.

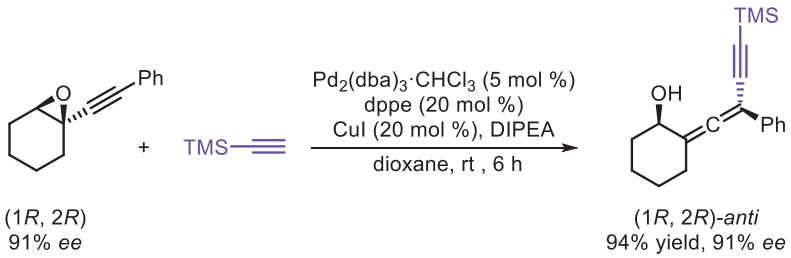
During the last two decades, alkynyl epoxides and alkyne diols have been employed for the synthesis of substituted *α*-allenols through S_N2'-type reactions in the presence of Grignard reagents or boronic acids. In 2003, the Fürstner research group employed alkynyl epoxides through an Fe-catalyzed cross-coupling reaction with Grignard reagents for the synthesis of tri- and tetra-substituted allenols (Scheme 12a).[57] With alkynyl epoxides having either terminal or non-terminal alkyne units, the reactions did not require added ligands and occurred instantaneously. The major products were the *syn*-configured 2,3-allenols which are opposite to those usually observed in reactions of alkynyl epoxides with organo-Cu reagents, except when carried out under "ligand-free" conditions and in the presence of excess TMSCl.[58] The authors proposed that the catalyst and/or the Grignard reagent may be coordinated to the oxygen atom of the oxirane ring, which then prospectively leads to the preferential formation of *syn*-configured 2,3-allenols.

In 2005, Yoshida and co-workers developed a Pd-catalyzed reaction of alkynyl epoxides with aryl boronic acids in which *anti*-substituted 4-aryl-2,3-allenols were obtained with high diastereoselectivity (Scheme 12b).[59] They proposed that in the first step of the reaction, regio- and stereoselective *anti*-S_N2' attack of the Pd (pre)catalyst on the alkynyl epoxides eventually leads to diastereoselective formation of *anti*-substituted 4-aryl-2,3-allenols. In 2009, the Murakami group described the stereoselective synthesis of *syn*-configured α-allenols from alkynyl epoxides and aryl boronic acids under Rh-catalysis (Scheme 12c).[60]

It was suggested that the high diastereoselectivity arises from the pre-coordination of the oxygen atom of the oxirane ring to the metal center.

Several years later, related and independent work from Sherburn and Dou showed that alkyne diols are efficient substrates in the synthesis of allenols (Scheme 12d-e).[61-62] In the case of the Pd-catalyzed Suzuki-Miyaura cross-coupling reaction from symmetrically substituted alkynes, only sterically hindered boronic acids were tolerated to avoid a two-fold addition process. A similar transformation using alkyne diols under Rh catalysis provided higher control toward "single addition" reactions. Less hindered boronic acids and unsymmetrically substituted alkyne diols were both tolerated in this latter protocol.

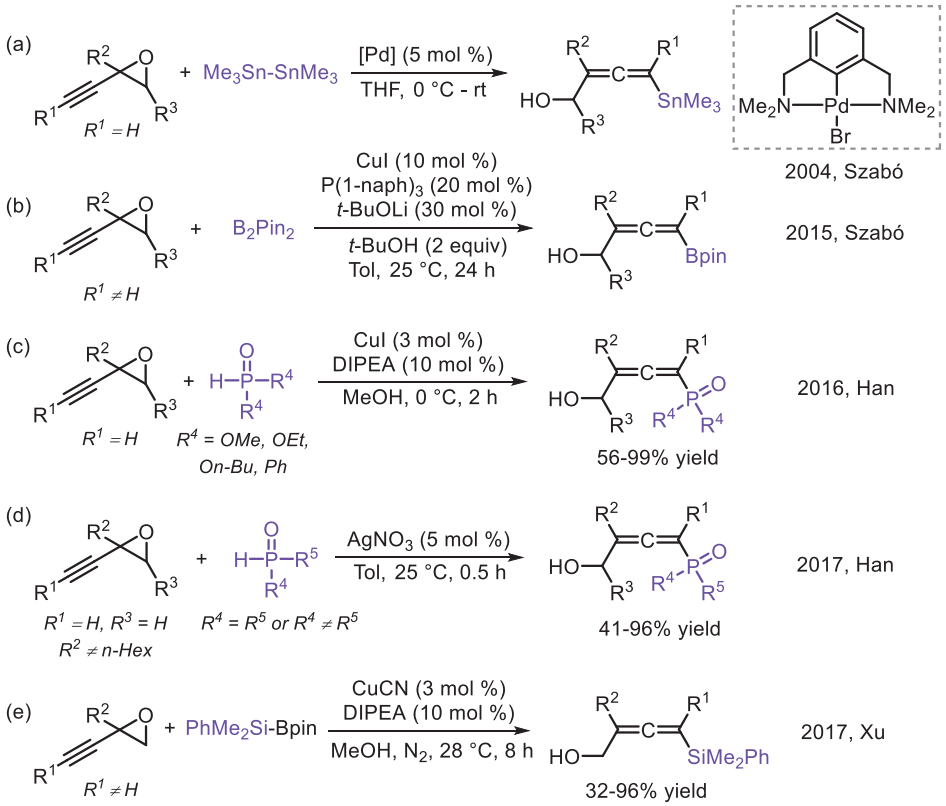
In 2016, Bäckvall and co-workers reported an Fe-catalyzed synthesis of allenols from alkyne diols having two different *O*-protecting groups and Grignard reagents (Scheme 12f–g).[63-64] The two alcohol units could be either on the opposite or same side of the alkyne moiety. A TBS-protected (TBS = *tert*-butyldimethylsilyl) hydroxyl group remained intact while the acetate-protected hydroxyl group acted as a leaving group.



Scheme 13. Synthesis of optically active α-allenol with terminal alkyne.

In 2007, Yoshida and co-workers developed a diastereoselective coupling of alkynyl epoxides with terminal alkynes under Pd and Cu co-catalysis (Scheme 13).[65] In the presence of dppe as the ligand, *anti*-substituted allenols were the predominant products. However, the stereoselectivity of the products could be altered by changing the ligand to PPh_3. An optically active *anti*-substituted allenol could be obtained from the reaction of an enantiomerically enriched alkynyl epoxide without loss of chirality.

While carbon-based nucleophiles such as Grignard reagents, boronic acids and terminal alkynes have been successfully employed for the synthesis of substituted α-allenol through S_N2'-type reactions with alkynyl epoxides or alkyne diols, hetero-atom based nucleophiles have not been widely utilized apart from a few, rare cases. Recently, several research groups started to focus on this latter kind of transformation for the synthesis of allenols with carbon-heteroatom bonds, which are not easily accessible through any other approach. In this context, hexamethylditin, P(O)H compounds, bis(pinacolato)diboron and silylboronates have been employed for the synthesis of Sn-, P-, B-, and Si-decorated allenols using different TM catalysts.



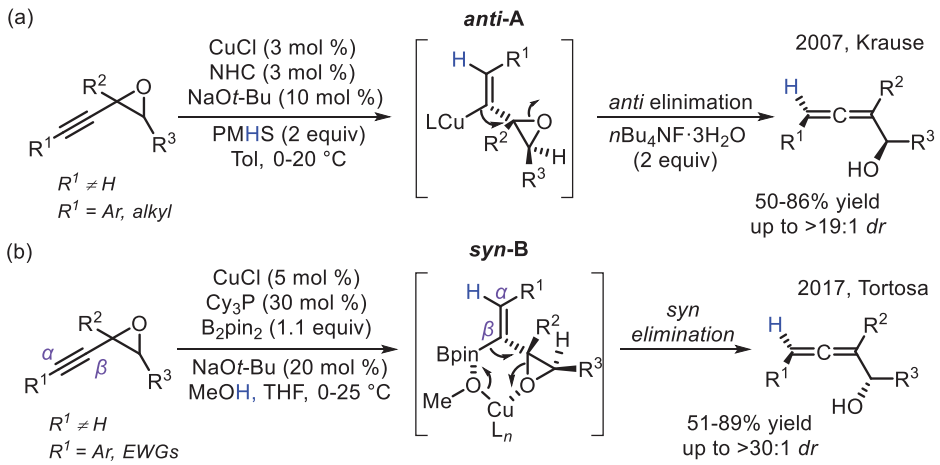
Scheme 14. Synthesis of hetero-decorated α-allenols via S_N2'-type reactions.

In 2005, Szabó and co-workers reported a Pd "pincer" catalyzed substitution of various alkynyl-substituted substrates using Sn- and Si-based bimetallic reagents.[66] During the examination of the scope of alkynyl substrates, they found that the epoxide ring-opening takes place with excellent regioselectivity providing Sn-decorated allenols, even though only three examples of alkynyl epoxides were tested (Scheme 14a). Ten years later, the same group developed a catalytic borylative ring-opening of alkynyl cyclopropanes under copper-catalyzed conditions, and extended the substrate scope to an alkynyl epoxide. In this case, a bulky $P(1\text{-naph})_3$ was required as ligand to obtain a monoborylated allenol, while other less bulky ligands could not prevent the formation of diborylated product (Scheme 14b).[67-72]

Along these lines, Han and co-workers developed an efficient Cu-catalyzed coupling of alkynyl epoxides with nucleophilic P(O)H derivatives that proceed via a unique nucleophilic interception of a Cu–acetylide intermediate to afford 4-phosphoryl 2,3-allenols in high yield under mild conditions (Scheme 14c).[73-74] However, the use of internal alkynyl epoxides was less successful and the target products could only be obtained in very low yields under the same reactions conditions. This observation indicated the feasibility of dual coordination of the Cu complex to both the alkyne and epoxide unit. Soon after, the same group developed a Ag-catalyzed, highly selective hydrophosphorylative ring-opening of alkynyl epoxides (Scheme 14d).[75] Comparing to the Cu-catalyzed method, the latter protocol expands the scope of P(O)H substrates including not only diphenyl phosphine oxide but also a variety of H-phosphonates and H-phosphinates amplifying the access to phosphorus-functionalized allenols. In the proposed mechanism, the coordination of a Ag(I) species to the epoxide ring and the carbon-carbon triple bonds is presented as key to enable this transformation.

In the last example (Scheme 14e) , a Cu-catalyzed silylation reaction of alkynyl epoxides is illustrated which was reported by Xu and co-workers.[76-81] Tri- and tetra-substituted, functionalized allenols could be obtained in good yields and under mild reaction conditions from internal alkynyl epoxides.

The smallest possible nucleophile (i.e., the hydride anion) has so far only played a minor role in Cu-mediated synthesis of *α*-allenols because the use of highly reactive metal hydrides as reagents causes regiochemistry problems and offers low functional group tolerance. There are a few excellent contributions that advanced this particular challenge. In 2007, Krause and co-workers developed an efficient method for the diastereoselective synthesis of α-allenols via CuH catalyzed S_N2' reduction of alkynyl epoxides (Scheme 15a).[82-84] The reaction proceeds through the formation of a vinyl-Cu species ***anti*-A** that undergoes an *anti*-*β*-oxygen elimination to produce the silyl-protected allenol with *anti*-stereoselectivity.



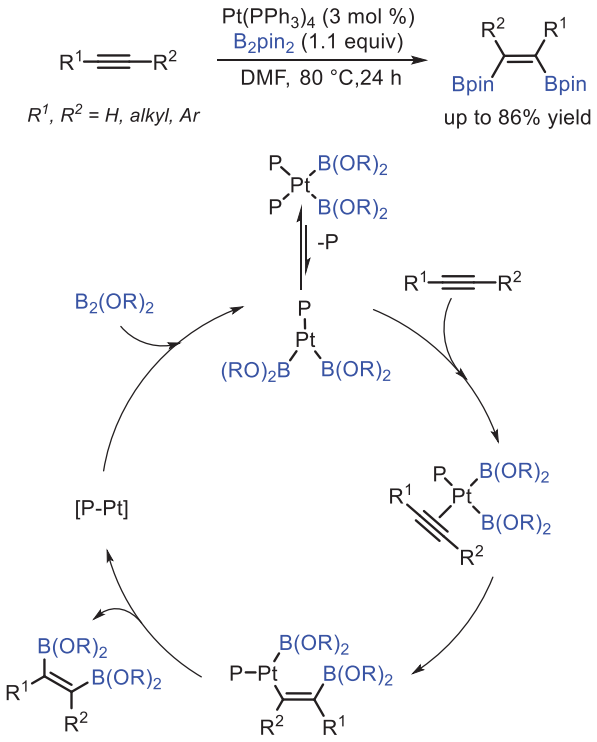
Scheme 15. Synthesis of *α*-allenols via Cu-catalyzed S_N2' reduction of alkynyl epoxides.

In 2017, Tortosa and co-workers reported that alkynyl epoxides undergo ring-opening through a *syn*-borohydride addition using MeOH as proton shuttle, followed by selective Cu-assisted *syn*-elimination (Scheme 15b).[85-86] A crucial *α*-epoxy vinyl boronate intermediate ***syn*-B** would participate in the following *syn*-*β*-oxygen elimination step to generate the allenol product, and this manifold was described in the literature for the first time. However, in order to control the Bpin addition to the *β*-position and introducing a hydrogen in the *α*-position after protonation with MeOH, internal alkynes equipped with

aromatic or electron-withdrawing groups were necessary. If the internal alkyne substrate is substituted by alkyl groups, ring-opening of the alkynyl epoxide could possibly generate an allenyl-boronate intermediate, which can undergo a second Cu-catalyzed borylation via an S_N2'-type mechanism to give a 1,2-diborylated butadiene.[71]

1.4 Mechanisms of synthesis of vicinal bis(boronate) esters from alkynes

Organoboronates have versatile reactivity, relative stability, and high functional group compatibility. They have gained extensive attention as versatile building blocks for the synthesis of complex molecules which play an important role in medicinal and materials chemistry.[87-108]



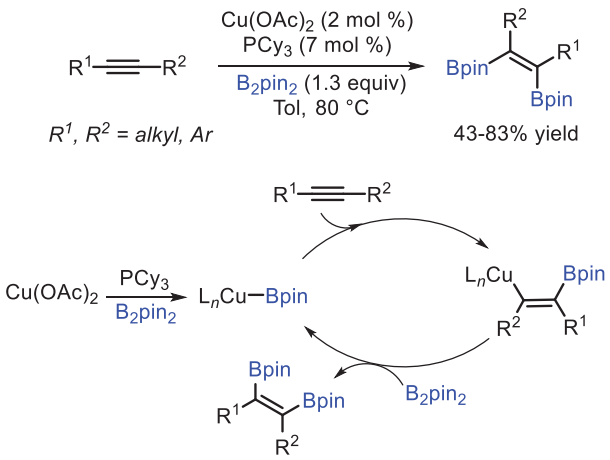
Scheme 16. Pt-catalyzed diboration of alkynes.

This section will focus on the mechanisms of synthesis of vicinal bis(boronate) esters which are usually obtained via selective 1,2-diboration of alkenes or alkynes. Especially, vinyl vicinal bis(boronate) esters can be used for regio- and stereoselective construction of multi-substituted olefins and 1,2-bifunctional compounds.

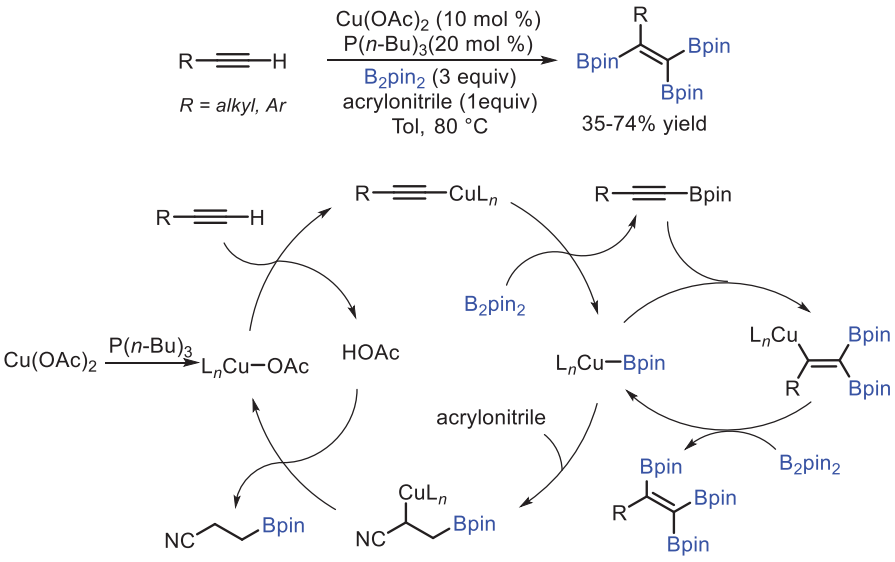
In 1993, the first metal catalyzed *cis*-1,2-diboration of alkynes was reported by Suzuki and Miyaura, who used $Pt(PPh_3)_4$ as catalyst (Scheme 16).[109-110] Hereafter, Marder and co-workers significantly improved this process by using the isolable and stable complex $Pt(PCy_3)(\eta^2\text{-}C_2H_4)_2$.[111-112] In general, platinum-catalyzed diboration of an alkyne involves the oxidative addition of Pt across the B–B bond, subsequent *cis*-insertion of C–C triple bonds into the Pt-B bond of the platinum bis(boryl) complex, following reductive elimination producing the vicinal bis(boronate) ester product and regenerates the catalyst for additional turnover. During the past two decades, Pd, Cu, Co, Fe, Zn and metal-free systems have been developed for the diboration of alkynes, which provide practical and economic alternatives for the Pt-catalyzed process.[108] Particularly, Cu-catalyzed borylation reactions of unsaturated carbon bonds have gained much attention in C–B formation chemistry. Nucleophilic boryl-Cu species, which are formed by σ-bond metathesis between Cu(I) complexes and diboron compounds, serve as key intermediates. Both mono- as well as diborylation pathways are feasible which thus represents a key chemo-selectivity aspect in these transformations.

Diboration of alkynes using Cu catalysis has been studied by several research groups. The first example of a Cu-catalyzed diboration reaction of C−C multiple bonds was reported by Pérez and Fernández in 2007.[113] Phenyl acetylene and diphenyl acetylene were diborated with the more reactive bis(catecholato)diboron (B_2cat_2) using Cu(I)-NHC complexes in THF at reflux temperature. Under these conditions, only the *cis*-diborated isomer product was obtained. Experimental and theoretical studies indicated that oxidative addition of the B−B bond to the Cu(I) (pre)catalyst is unlikely. In 2012, Yoshida and coworkers reported a more general and practical methodology for the diboration of internal

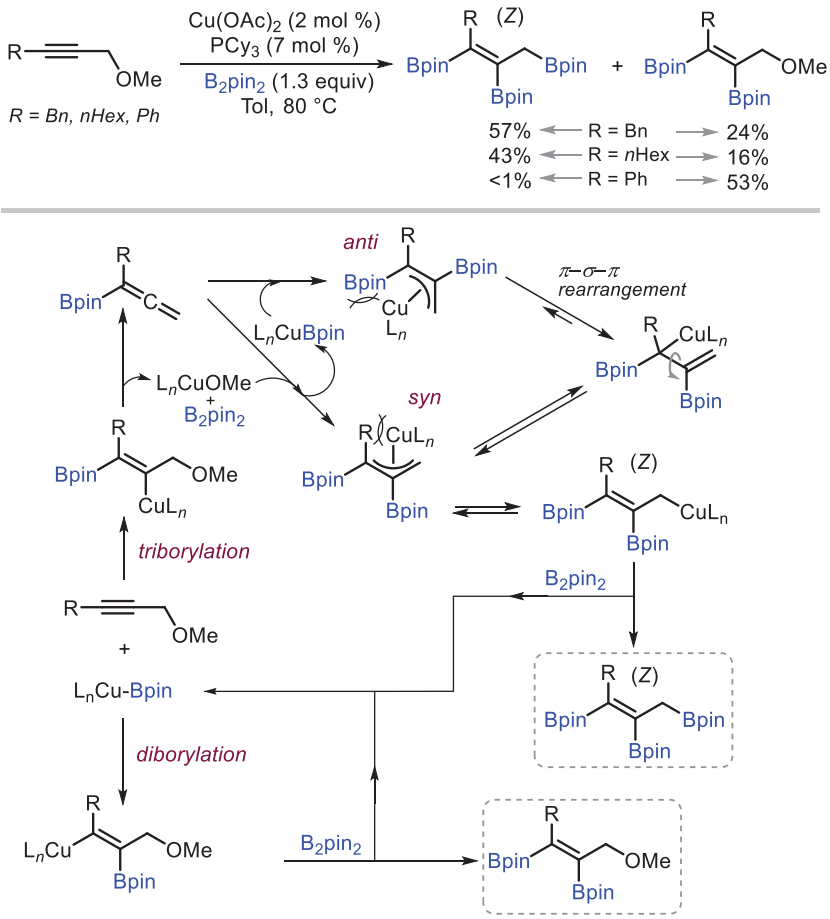
alkynes catalyzed by the combination of $Cu(OAc)_2$ and PCy_3, while using B_2pin_2 as the diboron reagent (Scheme 17).[114]



Scheme 17. Cu-catalyzed diboration of alkynes.



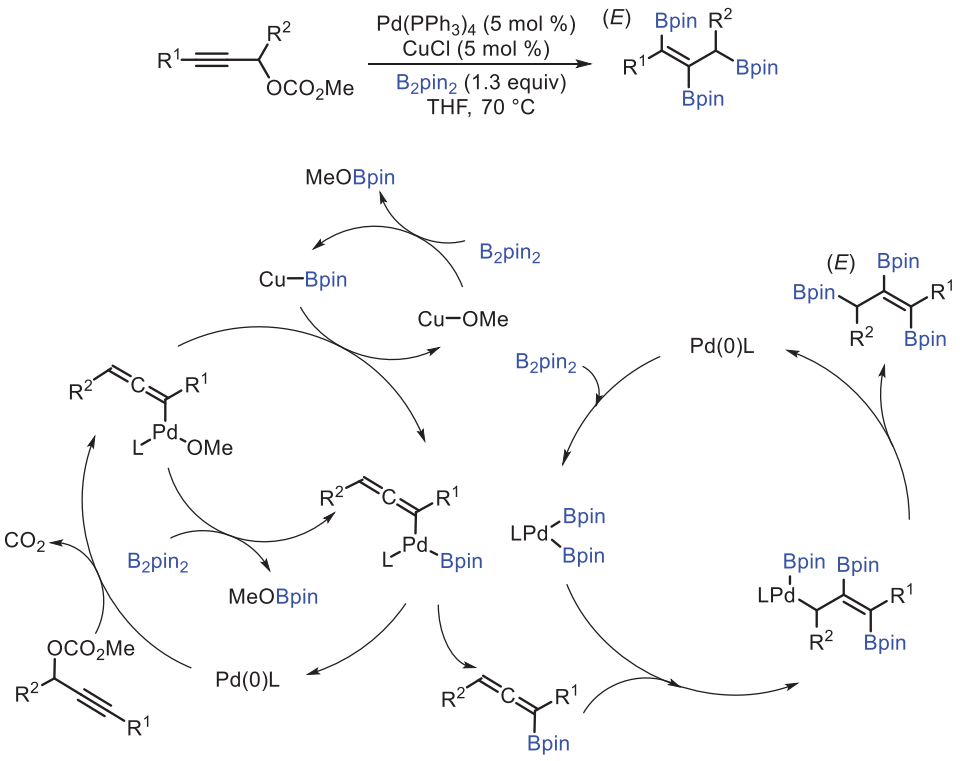
Scheme 18. Cu-catalyzed triboration of terminal alkynes.



Scheme 19. Cu-catalyzed synthesis of 1,2-(*Z*)-bisborylated alkenes and (*Z*)-alken-1,2,3-triboronates from propargylic ethers.

Internal alkynes bearing dialkyl-, diaryl-, or alkyl/aryl substituents and arynes underwent Cu-catalyzed diboration affording in all cases vicinal *cis*-diborylalkenes (or diborylarenes) in good yields. They proposed that the simultaneous interaction of copper acetate, the phosphine and the diboron reagent would benefit the formation of a key boryl-Cu(I) intermediate. Insertion of the C–C triple bond of the alkyne into the Cu-B bond would

give an organo-Cu species, and subsequent σ-bond metathesis delivers then the diborylated product and regenerates the boryl-Cu(I) species for further turnover.



Scheme 20. Bimetallic catalyzed synthesis of (*E*)-alken-1,2,3-triboronates from propargylic carbonates.

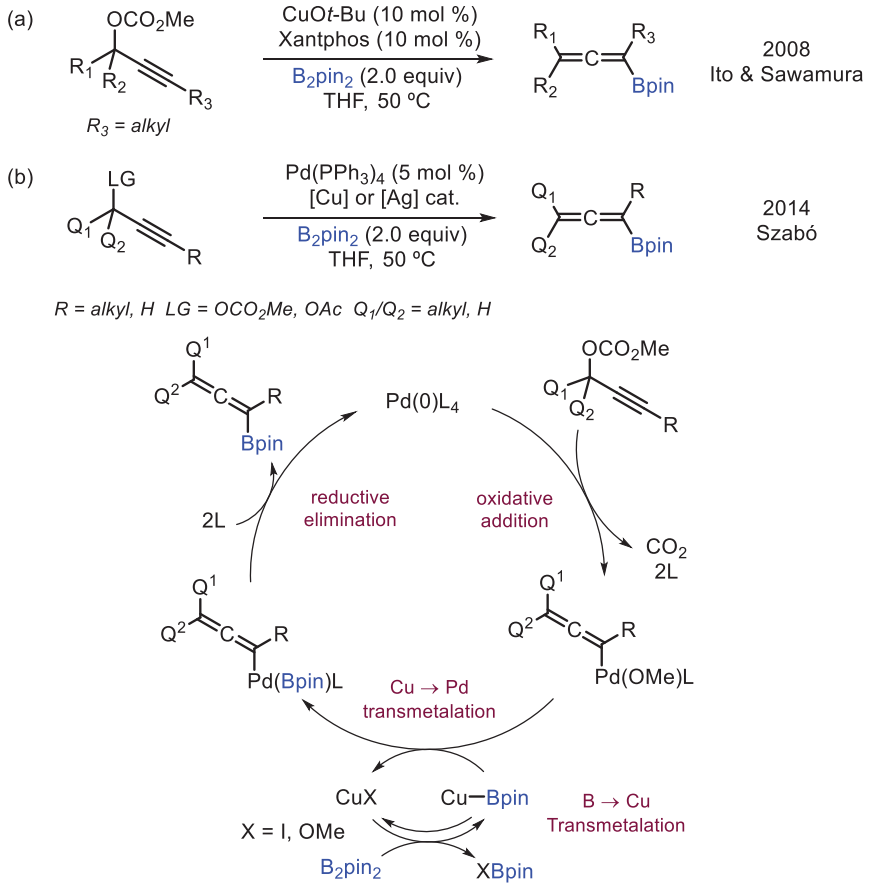
In 2020, Marder and co-workers reported a novel and straightforward Cu-catalyzed synthesis of 1,1,2-triborylalkenes by coupling of a diboron reagent with terminal alkynes (Scheme 18).[115] To avoid alkyne hydroboration, 1 equiv of acrylonitrile was added to suppress this potential side-reaction. In the envisioned manifold, first, [L_nCuOAc] is formed from $Cu(OAc)_2$ and the phosphine ligand through a net reduction. Then, the terminal alkyne is activated by [L_nCuOAc] to afford an alkynyl Cu intermediate. The latter undergoes a σ-bond metathesis with B_2pin_2 to afford an alkynyl boronate and Cu–boryl

complex. The alkynyl boronate, being reminiscent to internal alkynes, further undergoes diboration to afford the 1,1,2-triborylalkene type product. Since hydroboration of acrylonitrile is faster than that of alkynes, the presence of the additive effective suppress the alkyne hydroboration side reaction and improves the overall efficiency of the triboration process.

In Yoshida's work on the Cu/PCy_3-catalyzed 1,2-diboration of propargylic ethers produced (*Z*)-alken-1,2,3-triboronate via boryl-cupration and subsequent *σ*-bond metathesis of the π-allyl copper intermediates (Scheme 19).[114] These propargylic ethers, which are essentially internal alkynes, also lead conveniently to the formation of (*Z*)-diborylated products as competitive products under Cu catalysis. However, 1,2,3-tris(boronate) esters were noted as the major products, and the stereo-configuration (*Z*) was investigated by NOE. The triborylation product is suggested to arise from *σ*-bond metathesis of a *π*-allyl-Cu species (generated via an alkenyl Cu species) with the diboron compound attacking at the sterically less-hindered carbon center. The authors reasoned that the steric hindrance of the Bpin group in the *π*-allyl-Cu species dictates the regio- and stereoselectivity, but in this scenario it would be more likely that the (*E*)-alken-1,2,3-triboronate is formed instead of its (*Z*)-isomer if the π-allyl-Cu species were to be a η^1- rather than a η^3-allylic species. Unfortunately, the molecular structure of these 1,2,3-tris(boronate) esters could not be confirmed by X-ray analysis.

In 2017, Ma and co-workers developed a bimetallic catalyzed protocol for the preparation of (*E*)-alken-1,2,3-triboronates from propargylic carbonates via 1,2-allenyl boronate intermediates following their subsequent diboration (Scheme 20).[116] The reaction starts off with an S_N2'-type oxidative addition reaction between Pd(0) and the propargylic carbonates to give a 1,2-allenyl-Pd species. The latter undergoes transmetalation with the Cu-Bpin species (which is formed by transmetalation of the Cu (pre)catalyst with B_2pin_2) to generate a 1,2-allenyl-Pd(boryl) complex. Subsequent reductive elimination affords the 1,2-allenyl boronate. The diboration can be catalyzed by $Pd(PPh_3)_4$, similar to Pt catalyzed systems, while CuCl showed no effective diborylation activity. The insertion of the non-

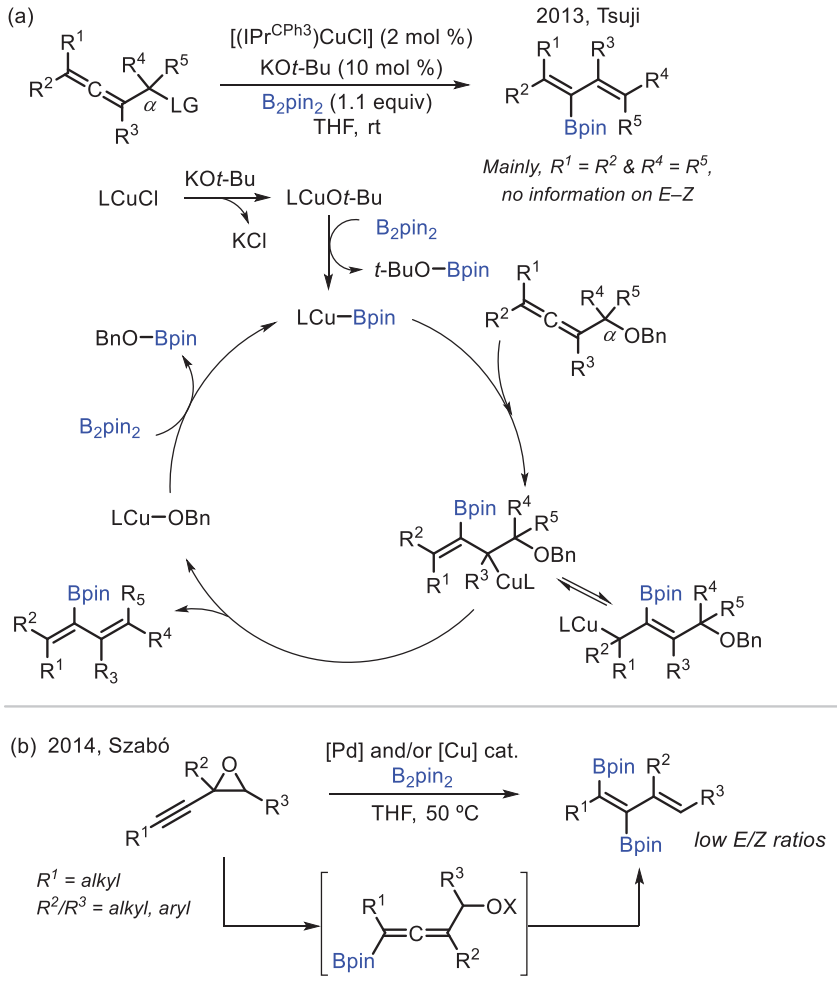
borylated C–C double bond of the 1,2-allenyl boronate into the Pd–B bond produces a η^1-allylic intermediate, which is considered to be key to the observed excellent regio- and stereoselectivity giving predominantly the (*E*)-alken-1,2,3-triboronate product.



Scheme 21. S_N2'-type substitution and S_N2'-type oxidative addition of propargylic system.

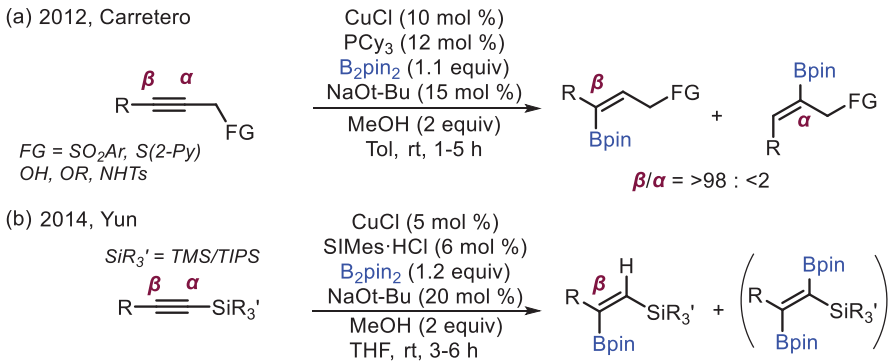
In 2008, Ito and Sawamura reported on the TM-catalyzed transformation of propargylic (linear) carbonates to allenyl boronates using B_2pin_2 as a boronate source in the presence of CuO*t*-Bu as (pre)catalyst (Scheme 21a).[72] The use of a bidentate ligand phosphine (Xantphos) may explain why this reaction does not lead to diboration as demonstrated in

Yoshida's work (Scheme 19).[114] These latter reactions are believed to start with an S_N2'-type substitution rather than an S_N2'-type oxidative addition. In 2014, Szabó and co-workers reported similar work based on bimetallic Pd/Cu and Pd/Ag catalytic systems (Scheme 21b).[71] Comparing with Ma's previous research (Scheme 20),[116] Szabó used almost the same reaction conditions and quite similar substrates, though the outcomes were different.



Scheme 22. Approaches to the synthesis of borylated 1,3-dienyl boranes.

Inspired by the pioneering studies from Ito, Sawamura, and co-workers on the Cu-catalyzed borylation of propargylic (linear) carbonates, Tsuji and co-workers developed a borylation of allenes bearing a suitable leaving group at the α-position to obtain 2-boryl 1,3-butadienes using Cu(NHC) catalysts (Scheme 22a).[117] As shown previously, insertion of one of the C–C double bonds of allene into the Cu–B bond can produce two types of η^1-allylic intermediates, which exchange by fast η^1-η^3 interconversion. β-Elimination of the benzyloxy moiety produces 2-boryl-1,3-butadienes and a Cu-alkoxide, [LCu-OBn]. Finally, α-bond metathesis of [LCu-OBn] with B_2pin_2 regenerates a boryl copper species, [LCu-Bpin]. Soon afterwards, Szabó and co-workers reported the ring-opening of propargyl epoxides with B_2pin_2 leading to 1,2-diborylated-1,3-butadienes, and this process likely goed through an allenyl-boronate intermediate (Scheme 22a).[71]



Scheme 23. Regioselective borylation of alkynes.

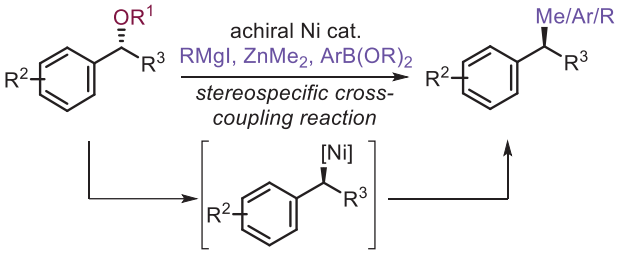
In 2012, Carretero and co-workers achieved the regioselective Cu(I)-catalyzed borylation of dialkyl internal alkynes with B_2pin_2 (Scheme 23a).[118] The presence of a propargylic polar group (OH, OR, SAr, SO_2Ar, or NHTs), in combination with PCy_3 as ligand, led to predominant β-borylation of the propargylic scaffold. The main reason for the observed regioselectivity seems to be the result of a subtle electronic bias rather than pure steric effects. Same year, McQuade and coworkers reported the site-selective reversal

from β to α in the borylation of internal propargylic alkynes using a bulkier Cu(NHC) catalyst and more hindered *p*-nitro-phenyl ether substrates.[119]

In 2014, Yun and co-workers reported that silyl groups act as directing groups for the introduction of boryl groups in the β-carbon (relative to the Si group) of internal silylalkynes. This chemistry is both driven by this directing group strategy and electronic effects (Scheme 23b).[120-121] In the case of aryl-substituted silylalkynes, the utilization of the bulkier Xantphos compared to $P(OEt)_3$ and SIMes·HCl prevents diboration and consequently provides a higher monoborylated product yield.[122] Substrates with electron-withdrawing substituents are converted with lower regioselectivity and their use results into the formation of higher amounts of (α-borylvinyl)silane compounds. This gives support for the hypothesis that the β-regioselectivity is under electronic rather than steric control.[123] In general, the Cu-catalyzed regioselectivity of borylation of internal alkyne substrates is mostly directed by electronic control except for cases of severe steric impediments.

1.5 Ni-catalyzed stereospecific cross-couplings and functionalization of alkynes

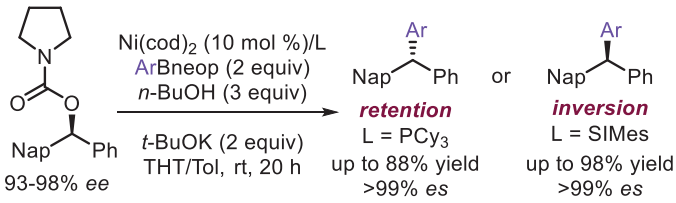
The development of Ni catalysis has created new synthetic potential and has enabled novel retrosynthetic schemes to access complex structures in short and economic steps.[124-130] The activation of benzylic C–O bonds has become a major topic of research, which can be ascribed to the crucial contributions of Ni-based catalysis.[131-133] Perhaps the most attractive feature of Ni catalysts is their seemingly inherent ability to promote stereoconvergent cross-coupling reactions, which allows access to highly enantioenriched products from their corresponding enantioenriched precursors.[134-135] The conversion of allylic alcohols share this particular feature, whereas Ni-catalyzed difunctionalization of alkynes has also rapidly emerged as a powerful tool for forging C–C bonds.[136-137] However, Ni-catalyzed S_N2'-type substitution reactions of propargylic derivatives with nucleophiles still remains unexplored as there is no precedent for *β*-oxygen elimination under Ni-catalysis.[138-139]



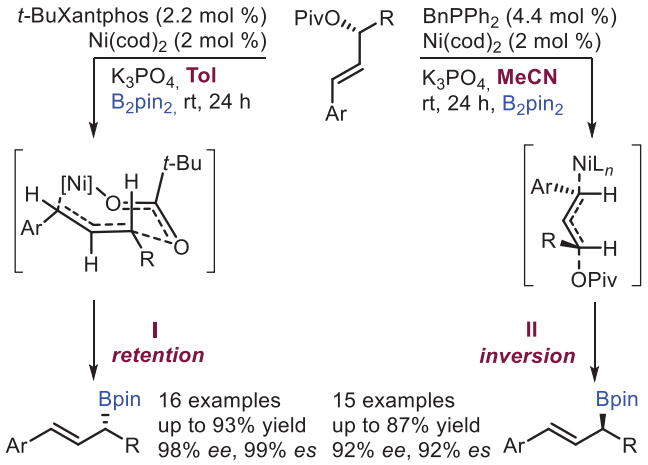
Scheme 24. Stereospecific Kumada, Negishi, and Suzuki coupling reactions of benzylic ethers.

Most reactions that involve alkyl electrophiles and low-valent Ni complexes proceed through alkyl radicals and thus are stereo-ablative; the correct chiral catalyst system can, however, favor the formation of a preferential enantiomer.[140-141] An example of this was reported by Jarvo and co-workers, who disclosed the first stereospecific Ni-catalyzed alkyl–alkyl cross-coupling reaction in 2011 (Scheme 24).[142] This method did not provoke racemization of the alkyl electrophiles, and provided clean inversion of the substrate

stereochemistry. Importantly, the starting materials (benzylic alcohols) can be generally prepared in high enantiomeric excess through a variety of asymmetric methods. A subsequent publication demonstrated the use of a 2-methoxyethyl ether moiety as a directing/activating group, which increased the ease of oxidative addition of the C–O bond to Ni.[143] Furthermore, subsequent publications by Jarvo[144-155] and Watson[156-161] demonstrated a series of stereospecific Kumada,[162] Negishi, and Suzuki reactions. This did not only showed a useful range of transmetalating agents, but also illustrated that a wider range of benzylic ethers and ester type substrates can participate, including methyl ethers, tetrahydropyrans, tetrahydrofurans, esters and lactones.



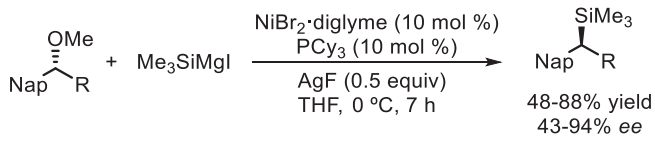
Scheme 25. Stereospecific Suzuki–Miyaura cross-coupling with inversion or retention.



Scheme 26. Solvent-controlled switch in stereospecific Miyaura borylation.

Another interesting example of Ni-catalysis was reported by Jarvo and co-workers in 2013 (Scheme 25).[145,163] They demonstrated the Suzuki–Miyaura cross-coupling of benzylic esters, carbonates, and carbamates with aryl boronic esters, which led to net retention or inversion of the substrate stereochemistry by tuning of the ligand. The use of PCy_3 provides net retention, whereas in the presence of SIMes formal inversion was observed.

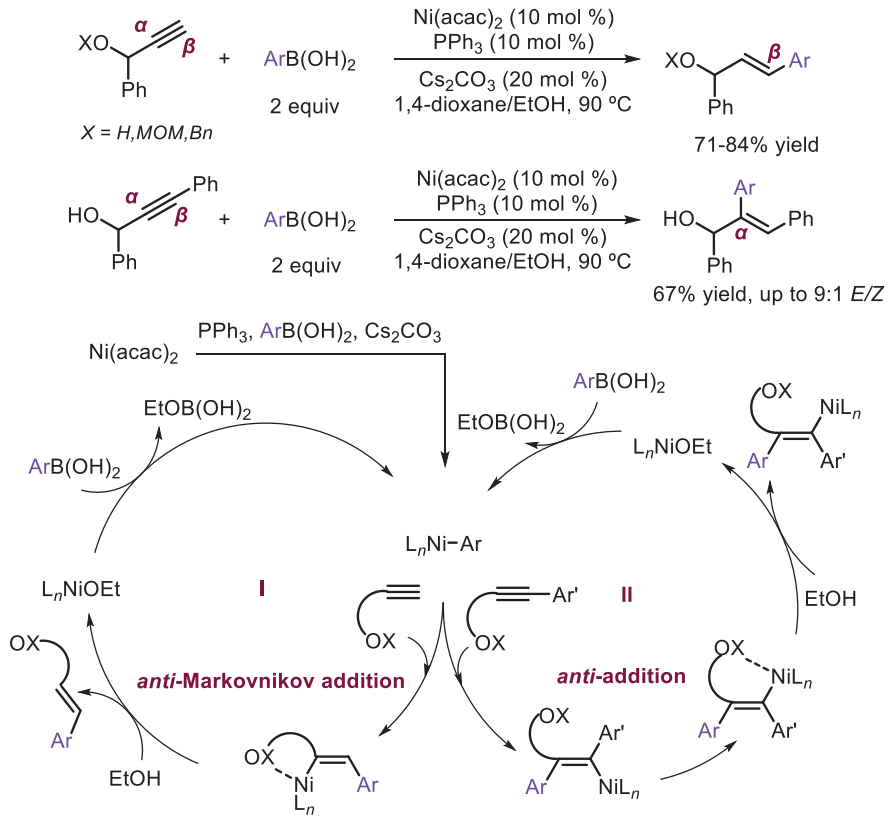
Another fascinating example was reported by Watson and co-workers in 2016. They developed a stereospecific cross-couplings of allylic alcohols to deliver highly enantioenriched allylic boronate esters (Scheme 26).[159, 164] One of the most interesting features of this process was the ability to dictate the stereochemical outcome of the reaction by changing the solvent. By using acetonitrile, the borylation occurred with inversion of the stereochemistry, but in toluene it let to stereoretention. A series of mechanistic studies were consistent with the oxidative addition being the key stereodetermining step. Under conditions favoring retention, less polar solvents gave higher levels of stereoretention, consistent with the hypothesis that a closed transition state favors retention. In more polar solvents, it is likely that the solvent also acted as a ligand for Ni, which prevents both pivalate coordination and the occurrence of a closed transition state.



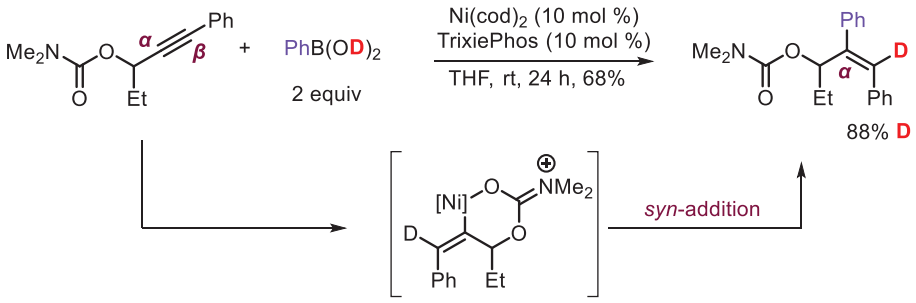
Scheme 27. Stereospecific silylation of benzylic ethers.

Enantiopure benzylic alcohols have almost exclusively been used to prepare other chiral compounds through Ni-catalysis with a focus on the construction of C−C bonds. In 2021, Rasappan and co-workers reported an AgF-assisted Ni catalyzed protocol that mediates the enantiospecific silylation of benzylic ethers (Scheme 27).[165-166] The authors introduced the economical Me_3SiMgI reagent in these enantiospecific cross-coupling reactions that proceed via C(sp^3)-O bond cleavage since the commonly employed and more expensive

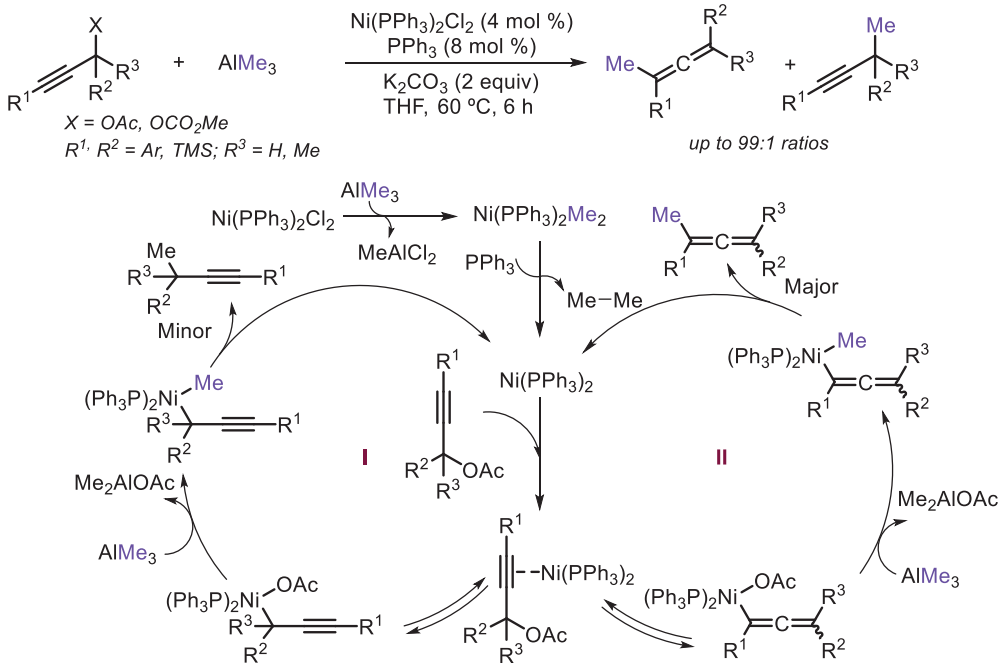
silylating agent (R_3Si-Bpin)[167-169] failed to furnish the desired product. Their methodology was compatible with a variety of functionalities including ketone, acetal, amide, boronic ester and aryl ether groups. However, this reaction did not overcome the requisite presence of a naphthyl group in the substrate to perform these stereospecific cross-couplings.[161]The same authors extended this methodology to enantiospecific silylation of allylic alcohol derivatives. They ruled out radical intermediate were present in the reaction mixture through radical clock experiments, and thus a homolytic cleavage of the C−OMe bond in this manifold seems unlikely.



Scheme 28. Ni-catalyzed addition of aryl boronic acids to phenyl acetylenes.



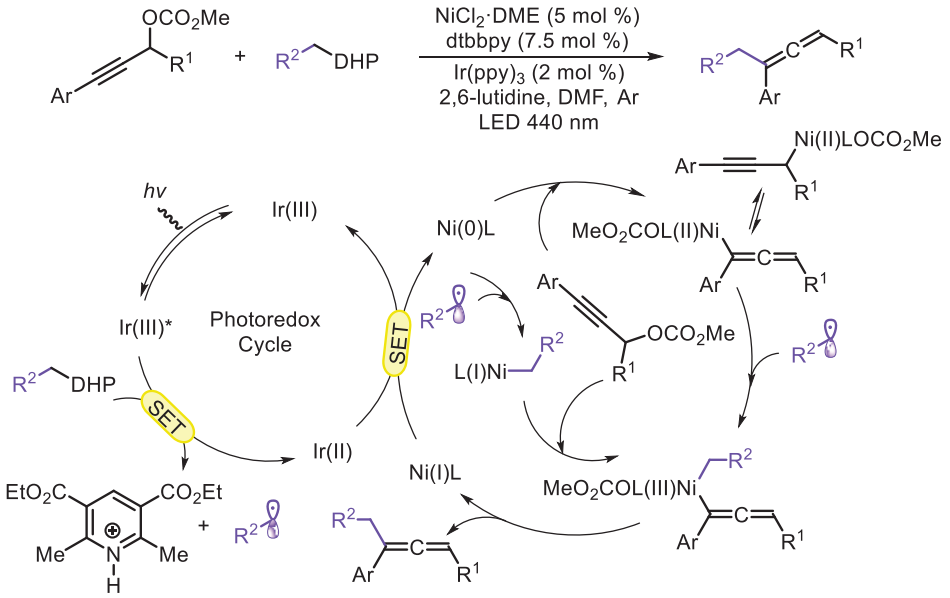
Scheme 29. Ni-catalyzed directed hydroarylation of phenyl acetylenes.



Scheme 30. Ni-catalyzed synthesis of multi-substituted allenes from propargylic esters.

Unlike allylic alcohol derivatives or benzylic ethers, the cleavage of the C–O bond in propargylic alcohols is rather rare under Ni catalysis, even though Ni-catalysts share similar characteristics compared to Pd or Cu catalysts. In 2017, Reddy and co-workers developed a Ni-catalyzed addition reaction of aryl boronic acids to directing group-tethered

alkynes (Scheme 28).[170-172] In the case of terminal propargylic alcohols, *anti*-Markovnikov addition of aryl boronic acids on terminal alkynes generates (*E*)-cinnamyl alcohol products. Contrary, *anti*-hydroarylation of benzylic propargyl alcohols delivers (*E*)-2,3-diphenylpropenol derivatives. The authors successfully trapped for both routes the vinyl-Ni intermediate with suitable Michael acceptors. In the case of the benzylic propargyl alcohol substrates, the authors believed that the addition resulted from a reverse regio-selection due to steric factors, which is contradictory to the Cu-catalyzed borylation of alkynes that proceeds under electronic rather than steric bias (see Scheme 23). Surprisingly, the transformation of MOM- and benzyl-protected propargylic alcohols delivered (*E*)-cinnamyl alcohols as a single isomer with high regio- and stereo-control and leaving the C–O bond intact.



Scheme 31. Ni-catalyzed synthesis of tri-substituted allenes from propargylic (linear) carbonates.

A few years ago, the Jarvo group reported on a regio- and stereoselective Ni-catalyzed hydroarylation of benzylic alkynes using propargylic carbamates as directing group

(Scheme 29).[173] They believed that a vinyl nickel intermediate (generated by carbamate-directed hydrometalation of the alkyne) was a crucial to deliver (*Z*)-2,3-diphenylpropenol derivatives. Compared with Cu or Pd catalysis, Ni complexes do not have rich history concerning *β*-oxygen eliminations.

Considering the nature of Ni catalysis, to the best of our knowledge, there is no precedent in the literature for a *β*-oxygen elimination with Ni in propargylic substitution reactions. Oxidative addition of a suitable propargylic precursor or surrogate to Ni(0) may give rise to the formation of an allenyl-Ni(II)-complex. This type of reaction is called S_N2'-type substitution. In 2018, Li and co-workers developed an efficient and simple route for the synthesis of multi-substituted allenes via a Ni-catalyzed S_N2' substitution reaction of propargylic esters with organic Al reagents (Scheme 30).[174] Control experiments demonstrated that the transmetalation and reduction of $Ni(PPh_3)_2Cl_2$ with $AlMe_3$ produces an active Ni(0) species, and then the Ni(0) complex activates the triple bond of the propargyl acetate substrate to form first a π-complex following allenyl Ni(II) complex formation via oxidative addition.

In 2021, Zhou and co-workers developed a regioselective alkylation of propargylic carbonates to afford trisubstituted allenes using 4-alkyl-1,4-dihydropyridine derivatives (1,4-DHPs) via a photoredox/Ni dual-catalyzed process (Scheme 31).[175] They proposed that the requisite Ni(0) species obtained by photoreduction promotes decarboxylation of propargylic carbonate to generate an allenyl-Ni(II) intermediate, which is then trapped by an alkyl radical to generate a Ni(III) intermediate. The product is then released and after reductive elimination. They could not rule out the possibility of the presence of an alkylated Ni(I) intermediate formed by the alkyl radical and the Ni(0) precatalyst, with oxidative addition of the propargylic carbonate and reductive elimination concluding this alternative pathway.

1.6 Thesis Aims

The development of TM-catalyzed propargylic substitution or S_N2'-type reaction of propargylic cyclic carbonates and related heterocycles has provided an efficient strategy to construct complex organic molecules and materials. Even though Cu catalysts have been shown to be very successful in promoting the asymmetric propargylic substitution of terminal alkyne-substituted cyclic carbonates via Cu−allenylidene intermediates, Cu-catalyzed S_N2'-type reactions of internal alkyne-substituted cyclic carbonates or similar heterocycles remains unexplored. Based on previous reports and recent achievements in our group, we envisioned that the development of Cu-promoted decarboxylative functionalization of (internal) alkyne-substituted cyclic carbonates with silylboron or diboron(4) reagents would potentially provide new reactivity paradigms while giving additional insights into the operating mode of the catalyst and delivering a more ample range of synthetically useful compounds. In addition, new catalytic protocols that can foster the easy preparation of enantioenriched products via stereospecific Ni-catalyzed reactions would also be an attractive target.

Taking into account that the state of the art and our previous experience and knowledge on the conversion of terminal alkynyl cyclic carbonates, the aims of this thesis are defined as follows:

(1) The design of a general procedure for the preparation of highly versatile and modular internal alkyne-substituted cyclic carbonates.

(2) To explore the Cu-catalyzed, decarboxylative silylation of alkyne-functionalized cyclic carbonate substrates with silylboron reagents.

(3) To examine the Cu-mediated borylation of internal alkynyl cyclic carbonates.

(4) To develop an efficient Ni-catalyzed activation and silylation protocol of both racemic and enantioenriched internal alkynyl cyclic carbonates.

1.7 References

1. Ault, A., *J. Chem. Educ.* **2002**, *79*, 572.
2. Casey, C. P., *J. Chem. Educ.* **2006**, *83*, 192.
3. 'Nobel Prize in Chemistry 2010: Palladium-Catalyzed Cross Couplings in Organic Synthesis', The Royal Swedish Academy of Sciences, Stockholm, Sweden, 6th October, **2010**: https://www.nobelprize.org/prizes/chemistry/2010/summary/.
4. Guram, A. S.; Buchwald, S. L., *J. Am. Chem. Soc.* **1994**, *116*, 7901.
5. Guram, A. S.; Rennels, R. A.; Buchwald, S. L., *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 1348.
6. Paul, F.; Patt, J.; Hartwig, J. F., *J. Am. Chem. Soc.* 1994, *116*, 5969.
7. Louie, J.; Hartwig, J. F., *Tetrahedron Lett.* **1995**, *36*, 3609.
8. Hartwig, J. F., *Acc. Chem. Res.* **1998**, *31*, 852.
9. Wolfe, J. P.; Wagaw, S.; Marcoux, J.-F.; Buchwald, S. L., *Acc. Chem. Res.* **1998**, *31*, 805.
10. Ruiz-Castillo, P.; Buchwald, S. L., *Chem. Rev.* **2016**, *116*, 12564.
11. Ullmann, F., *Ber. Dtsch. Chem. Ges.* **1903**, *36*, 2382.
12. Qiao, J. X.; Lam, P. Y. S., Recent Advances in Chan–Lam Coupling Reaction: Copper-Promoted C–Heteroatom Bond Cross-Coupling Reactions with Boronic Acids and Derivatives. In *Boronic Acids*, **2011**; pp 315.
13. Ma, D.; Cai, Q.; Zhang, H., *Org. Lett.* **2003**, *5*, 2453.
14. Frazzoli, C.; Cammarone, R.; Caroli, S., *Food Addit. Contam.* **2007**, *24*, 546.
15. Tsuji, H.; Kawatsura, M., *Asian J. Org. Chem.* **2020**, *9*, 1924.
16. Müller, D. S.; Marek, I., *Chem. Soc. Rev.* **2016**, *45*, 4552.
17. Roh, S. W.; Choi, K.; Lee, C., *Chem. Rev.* **2019**, *119*, 4293.
18. Alexakis, A.; Marek, I.; Mangeney, P.; Normant, J. F., *Tetrahedron Lett.* **1989**, *30*, 2387.
19. Macdonald, T. L.; Reagan, D. R.; Brinkmeyer, R. S., *J. Org. Chem.* **1980**, *45*, 4740.
20. Darcel, C.; Bruneau, C.; Dixneuf, P. H., *Synlett* **1996**, *1996*, 218.

21. Darcel, C.; Bruneau, C.; Albert, M.; Dixneuf, P. H., *Chem. Commun.* **1996**, 919.
22. Darcel, C.; Bruneau, C.; Dixneuf, P. H., J. Chem. Soc., *Chem. Commun.* **1994**, 1845.
23. Darcel, C.; Bartsch, S.; Bruneau, C.; Dixneuf, P. H., *Synlett* **1994**, *1994*, 457.
24. Tian, L.; Gong, L.; Zhang, X., *Adv. Synth. Catal.* **2018**, *360*, 2055.
25. Zhang, Y.-C.; Zhang, B.-W.; Geng, R.-L.; Song, *J., Org. Lett.* **2018**, *20*, 7907.
26. Gómez, J. E.; Cristòfol, À.; Kleij, A. W., *Angew. Chem. Int. Ed.* **2019**, *58*, 3903.
27. Zhang, Z.-J.; Zhang, L.; Geng, R.-L.; Song, J.; Chen, X.-H.; Gong, L.-Z., *Angew. Chem. Int. Ed.* **2019**, *58*, 12190.
28. Song, J.; Zhang, Z.-J.; Gong, L.-Z., *Angew. Chem. Int. Ed.* **2017**, *56*, 5212.
29. Lu, W.-Y.; Wang, Y.; You, Y.; Wang, Z.-H.; Zhao, J.-Q.; Zhou, M.-Q.; Yuan, W.-C., *J. Org. Chem.* **2021**, *86*, 1779.
30. Xu, Y.-W.; Hu, X.-P., *Org. Lett.* **2019**, *21*, 8091.
31. Zhang, J.; Ni, T.; Yang, W.-L.; Deng, W.-P., *Org. Lett.* **2020**, *22*, 4547.
32. Guo, W.; Zuo, L.; Cui, M.; Yan, B.; Ni, S., *J. Am. Chem. Soc.* **2021**, *143*, 7629.
33. Gómez, J. E.; Guo, W.; Gaspa, S.; Kleij, A. W., *Angew. Chem. Int. Ed.* **2017**, *56*, 15035.
34. Tang, X.; Woodward, S.; Krause, N., *Eur. J. Org. Chem.* **2009**, 2836.
35. Lu, W.-Y.; You, Y.; Li, T.-T.; Wang, Z.-H.; Zhao, J.-Q.; Yuan, W.-C., *J. Org. Chem.* **2021**, *86*, 6711.
36. Yu, S.; Ma, S., *Angew. Chem. Int. Ed.* **2012**, *51*, 3074.
37. Yu, S.; Ma, S., *Chem. Commun.* **2011**, *47*, 5384.
38. Li, G.; Huo, X.; Jiang, X.; Zhang, W., *Chem. Soc. Rev.* **2020**, *49*, 2060.
39. Lu, T.; Lu, Z.; Ma, Z.-X.; Zhang, Y.; Hsung, R. P., *Chem. Rev.* **2013**, *113*, 4862.
40. Hoffmann-Röder, A.; Krause, N., *Angew. Chem. Int. Ed.* **2004**, *43*, 1196.
41. Ogasawara, M., *Tetrahedron: Asymmetry* **2009**, *20*, 259.
42. Rivera-Fuentes, P.; Diederich, F., *Angew. Chem. Int. Ed.* **2012**, *51*, 2818.
43. Neff, R. K.; Frantz, D. E., *ACS Catal.* **2014**, *4*, 519.
44. Chu, W.-D.; Zhang, Y.; Wang, J., *Catal. Sci. Technol.* **2017**, *7*, 4570.

45. Krause, N.; Hoffmann-Röder, A., *Tetrahedron* **2004**, *60*, 11671.
46. Huang, X.; Ma, S., *Acc. Chem. Res.* **2019**, *52*, 1301.
47. Ye, J.; Ma, S., *Acc. Chem. Res.* **2014**, *47*, 989.
48. Ma, S., *Acc. Chem. Res.* **2009**, *42*, 1679.
49. Lechel, T.; Pfrengle, F.; Reissig, H.-U.; Zimmer, R., *ChemCatChem* **2013**, *5*, 2100.
50. Zimmer, R.; Dinesh, C. U.; Nandanan, E.; Khan, F. A., *Chem. Rev.* **2000**, *100*, 3067.
51. Muñoz, M. P., *Chem. Soc. Rev.* **2014**, *43*, 3164.
52. Qiu, G.; Zhang, J.; Zhou, K.; Wu, J., *Tetrahedron* **2018**, *74*, 7290.
53. Yang, B.; Qiu, Y.; Bäckvall, J.-E., *Acc. Chem. Res.* **2018**, *51*, 1520.
54. Soriano, E.; Fernández, I., *Chem. Soc. Rev.* **2014**, *43*, 3041.
55. Aubert, C.; Fensterbank, L.; Garcia, P.; Malacria, M.; Simonneau, A., *Chem. Rev.* **2011**, *111*, 1954.
56. Alonso, J. M.; Almendros, P., *Chem. Rev.* **2021**, *121*, 4193.
57. Fürstner, A.; Méndez, M., *Angew. Chem. Int. Ed.* **2003**, *42*, 5355.
58. Alexakis, A.; Marek, I.; Mangeney, P.; Normant, J. F., *Tetrahedron* **1991**, *47*, 1677.
59. Yoshida, M.; Ueda, H.; Ihara, M., *Tetrahedron Lett.* **2005**, *46*, 6705.
60. Miura, T.; Shimada, M.; de Mendoza, P.; Deutsch, C.; Krause, N.; Murakami, M., *J. Org. Chem.* **2009**, *74*, 6050.
61. Green, N. J.; Willis, A. C.; Sherburn, M. S., *Angew. Chem. Int. Ed.* **2016**, *55*, 9244.
62. Xing, J.; Zhu, Y.; Lin, X.; Liu, N.; Shen, Y.; Lu, T.; Dou, X., *Adv. Synth. Catal.* **2018**, *360*, 1595.
63. Kessler, S. N.; Hundemer, F.; Bäckvall, J.-E., *ACS Catal.* **2016**, *6*, 7448.
64. Kessler, S. N.; Bäckvall, J.-E., *Angew. Chem. Int. Ed.* **2016**, *55*, 3734.
65. Yoshida, M.; Hayashi, M.; Shishido, K., *Org. Lett.* **2007**, *9*, 1643.
66. Kjellgren, J.; Sundén, H.; Szabó, K. J., *J. Am. Chem. Soc.* **2005**, *127*, 1787.
67. Zhao, J.; Szabó, K. J., *Angew. Chem. Int. Ed.* **2016**, *55*, 1502.
68. Yang, Y.; Szabó, K. J., *J. Org. Chem.* **2016**, *81*, 250.

69. Mao, L.; Bertermann, R.; Emmert, K.; Szabó, K. J.; Marder, T. B., *Org. Lett.* **2017**, *19*, 6586.
70. Zhao, J.; Jonker, S. J. T.; Meyer, D. N.; Schulz, G.; Tran, C. D.; Eriksson, L.; Szabó, K. J., *Chem. Sci.* **2018**, *9*, 3305.
71. Zhao, T. S. N.; Yang, Y.; Lessing, T.; Szabó, K. J., *J. Am. Chem. Soc.* **2014**, *136*, 7563.
72. Ito, H.; Sasaki, Y.; Sawamura, M., *J. Am. Chem. Soc.* **2008**, *130*, 15774.
73. Shen, R.; Yang, J.; Zhao, H.; Feng, Y.; Zhang, L.; Han, L.-B., *Chem. Commun.* **2016**, *52*, 11959.
74. Xu, Q.; Han, L.-B., *J. Organomet. Chem.* **2011**, *696*, 130.
75. Shen, R.; Yang, J.; Zhang, M.; Han, L.-B., *Adv. Synth. Catal.* **2017**, *359*, 3626.
76. Chang, X.-H.; Liu, Z.-L.; Luo, Y.-C.; Yang, C.; Liu, X.-W.; Da, B.-C.; Li, J.-J.; Ahmad, T.; Loh, T.-P.; Xu, Y.-H., *Chem. Commun.* **2017**, *53*, 9344.
77. Wang, M.; Liu, Z.-L.; Zhang, X.; Tian, P.-P.; Xu, Y.-H.; Loh, T.-P., *J. Am. Chem. Soc.* **2015**, *137*, 14830.
78. Liu, Z.-L.; Yang, C.; Xue, Q.-Y.; Zhao, M.; Shan, C.-C.; Xu, Y.-H.; Loh, T.-P., *Angew. Chem. Int. Ed.* **2019**, *58*, 16538.
79. Zhao, M.; Shan, C.-C.; Wang, Z.-L.; Yang, C.; Fu, Y.; Xu, Y.-H., *Org. Lett.* **2019**, *21*, 6016.
80. Yang, C.; Liu, Z.-L.; Dai, D.-T.; Li, Q.; Ma, W.-W.; Zhao, M.; Xu, Y.-H., *Org. Lett.* **2020**, *22*, 1360.
81. Trost, B. M.; Tour, J. M., *J. Org. Chem.* **1989**, *54*, 484.
82. Deutsch, C.; Lipshutz, B. H.; Krause, N., *Angew. Chem. Int. Ed.* **2007**, *46*, 1650.
83. Reeker, H.; Norrby, P.-O.; Krause, N., *Organometallics* **2012**, *31*, 8024.
84. Zhong, C.; Sasaki, Y.; Ito, H.; Sawamura, M., *Chem. Commun.* **2009**, 5850.
85. Jarava-Barrera, C.; Parra, A.; Amenós, L.; Arroyo, A.; Tortosa, M., *Chem. Eur. J* **2017**, *23*, 17478.
86. Amenós, L.; Nóvoa, L.; Trulli, L.; Arroyo-Bondía, A.; Parra, A.; Tortosa, M., *ACS Catal.* **2019**, *9*, 6583.

87. Nallagonda, R.; Padala, K.; Masarwa, A., *Org. Biomol. Chem.* **2018**, *16*, 1050.
88. Suzuki, A., *Acc. Chem. Res.* **1982**, *15*, 178.
89. Fyfe, J. W. B.; Watson, A. J. B., *Chem* **2017**, *3*, 31.
90. He, Z.; Hu, Y.; Xia, C.; Liu, C., *Org. Biomol. Chem.* **2019**, *17*, 6099.
91. Gava, R.; Fernández, E., *Org. Biomol. Chem.* **2019**, *17*, 6317.
92. Yoshida, H., *ACS Catal.* **2016**, *6*, 1799.
93. Zhao, F.; Jia, X.; Li, P.; Zhao, J.; Zhou, Y.; Wang, J.; Liu, H., *Org. Chem. Front.* **2017**, *4*, 2235.
94. Beletskaya, I.; Moberg, C., *Chem. Rev.* **2006**, *106*, 2320.
95. Yun, J., *Asian J. Org. Chem.* **2013**, *2*, 1016.
96. Ansell, M. B.; Navarro, O.; Spencer, J., *Coord. Chem. Rev.* **2017**, *336*, 54.
97. Wang, X.; Wang, Y.; Huang, W.; Xia, C.; Wu, L., *ACS Catal.* **2021**, *11*, 1.
98. Barbeyron, R.; Benedetti, E.; Cossy, J.; Vasseur, J.-J.; Arseniyadis, S.; Smietana, M., *Tetrahedron* **2014**, *70*, 8431.
99. Takaya, J.; Iwasawa, N., *ACS Catal.* **2012**, *2*, 1993.
100. Ishiyama, T.; Miyaura, N., *Chem. Rec.* **2004**, *3*, 271.
101. Nguyen, V. D.; Nguyen, V. T.; Jin, S.; Dang, H. T.; Larionov, O. V., *Tetrahedron* **2019**, *75*, 584.
102. Hemming, D.; Fritzemeier, R.; Westcott, S. A.; Santos, W. L.; Steel, P. G., *Chem. Soc. Rev.* **2018**, *47*, 7477.
103. Carreras, J.; Caballero, A.; Pérez, P. J., *Chem. Asian J.* **2019**, *14*, 329.
104. Manna, S.; Das, K. K.; Aich, D.; Panda, S., *Adv. Synth. Catal.* **2021**, *363*, 2444.
105. Dewhurst, R. D.; Neeve, E. C.; Braunschweig, H.; Marder, T. B., *Chem. Commun.* **2015**, *51*, 9594.
106. Neeve, E. C.; Geier, S. J.; Mkhalid, I. A. I.; Westcott, S. A.; Marder, T. B., *Chem. Rev.* **2016**, *116*, 9091.
107. Sandford, C.; Aggarwal, V. K., *Chem. Commun.* **2017**, *53*, 5481.
108. Yang, X.; Kalita, S. J.; Maheshuni, S.; Huang, Y.-Y., *Coord. Chem. Rev.* **2019**, *392*, 35.

109. Ishiyama, T.; Matsuda, N.; Miyaura, N.; Suzuki, A., *J. Am. Chem. Soc.* **1993**, *115*, 11018.
110. Ishiyama, T.; Matsuda, N.; Murata, M.; Ozawa, F.; Suzuki, A.; Miyaura, N., *Organometallics* **1996**, *15*, 713.
111. Lesley, G.; Nguyen, P.; Taylor, N. J.; Marder, T. B.; Scott, A. J.; Clegg, W.; Norman, N. C., *Organometallics* **1996**, *15*, 5137.
112. Thomas, R. L.; Souza, F. E. S.; Marder, T. B., J. Chem. Soc., *Dalton Trans.* **2001**, 1650.
113. Lillo, V.; Fructos, M. R.; Ramírez, J.; Braga, A. A. C.; Maseras, F.; Díaz-Requejo, M. M.; Pérez, P. J.; Fernández, E., *Chem. Eur. J* **2007**, *13*, 2614.
114. Yoshida, H.; Kawashima, S.; Takemoto, Y.; Okada, K.; Ohshita, J.; Takaki, K., *Angew. Chem. Int. Ed.* **2012**, *51*, 235.
115. Liu, X.; Ming, W.; Friedrich, A.; Kerner, F.; Marder, T. B., *Angew. Chem. Int. Ed.* **2020**, *59*, 304.
116. Yang, Z.; Cao, T.; Han, Y.; Lin, W.; Liu, Q.; Tang, Y.; Zhai, Y.; Jia, M.; Zhang, W.; Zhu, T.; Ma, S., *Chin. J. Chem.* **2017**, *35*, 1251.
117. Semba, K.; Fujihara, T.; Terao, J.; Tsuji, Y., *Angew. Chem. Int. Ed.* **2013**, *52*, 12400.
118. Moure, A. L.; Gómez Arrayás, R.; Cárdenas, D. J.; Alonso, I.; Carretero, J. C., *J. Am. Chem. Soc.* **2012**, *134*, 7219.
119. Park, J. K.; Ondrusek, B. A.; McQuade, D. T., *Org. Lett.* **2012**, *14*, 4790.
120. Chae, Y. M.; Bae, J. S.; Moon, J. H.; Lee, J. Y.; Yun, J., *Adv. Synth. Catal.* **2014**, *356*, 843.
121. Kim, Y. E.; Li, D.; Yun, J., *Dalton Trans.* **2015**, *44*, 12091.
122. Jung, H.-Y.; Yun, J., *Org. Lett.* **2012**, *14*, 2606.
123. Kim, H. R.; Yun, J., *Chem. Commun.* **2011**, *47*, 2943.
124. Rosen, B. M.; Quasdorf, K. W.; Wilson, D. A.; Zhang, N.; Resmerita, A.-M.; Garg, N. K.; Percec, V., *Chem. Rev.* **2011**, *111*, 1346.
125. Butt, N. A.; Zhang, W., *Chem. Soc. Rev.* **2015**, *44*, 7929.

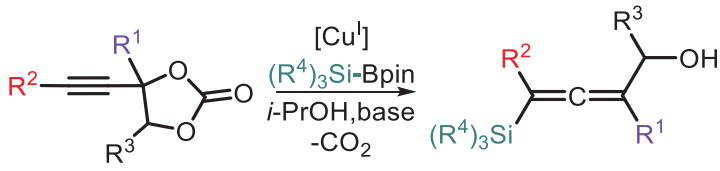
126. Wang, S.-S.; Yang, G.-Y., *Catal. Sci. Technol.* **2016**, *6*, 2862.
127. Diccianni, J. B.; Diao, T., *Trends Chem.* **2019**, *1*, 830.
128. Clevenger, A. L.; Stolley, R. M.; Aderibigbe, J.; Louie, J., *Chem. Rev.* **2020**, *120*, 6124.
129. Liu, Y.-H.; Xia, Y.-N.; Shi, B.-F., *Chin. J. Chem.* **2020**, *38*, 635.
130. Zhang, S.-Q.; Hong, X., *Acc. Chem. Res.* **2021**, *54*, 2158.
131. Tollefson, E. J.; Hanna, L. E.; Jarvo, E. R., *Acc. Chem. Res.* **2015**, *48*, 2344.
132. Li, X.; Hong, X., J. *Organomet. Chem.* **2018**, *864*, 68.
133. Cornella, J.; Zarate, C.; Martin, R., *Chem. Soc. Rev.* **2014**, *43*, 8081.
134. Tasker, S. Z.; Standley, E. A.; Jamison, T. F., *Nature* **2014**, *509*, 299.
135. Standley, E. A.; Tasker, S. Z.; Jensen, K. L.; Jamison, T. F., *Acc. Chem. Res.* **2015**, *48*, 1503.
136. Xu, J.; Bercher, O. P.; Talley, M. R.; Watson, M. P., *ACS Catal.* **2021**, *11*, 1604.
137. Derosa, J.; Apolinar, O.; Kang, T.; Tran, V. T.; Engle, K. M., *Chem. Sci.* **2020**, *11*, 4287.
138. Luo, Y.; Gutiérrez-Bonet, Á.; Matsui, J. K.; Rotella, M. E.; Dykstra, R.; Gutierrez, O.; Molander, G. A., *ACS Catal.* **2019**, *9*, 8835.
139. Diallo, A. G.; Roy, D.; Gaillard, S.; Lautens, M.; Renaud, J.-L., *Org. Lett.* **2020**, *22*, 2442.
140. Lucas, E. L.; Jarvo, E. R., *Nat. Rev. Chem.* **2017**, *1*, 0065.
141. Lucas, E. L.; Jarvo, E. R., *Acc. Chem. Res.* **2018**, *51*, 567.
142. Taylor, B. L. H.; Swift, E. C.; Waetzig, J. D.; Jarvo, E. R., *J. Am. Chem. Soc.* **2011**, *133*, 389.
143. Greene, M. A.; Yonova, I. M.; Williams, F. J.; Jarvo, E. R., *Org. Lett.* **2012**, *14*, 4293.
144. Taylor, B. L. H.; Harris, M. R.; Jarvo, E. R., *Angew. Chem. Int. Ed.* **2012**, *51*, 7790.
145. Harris, M. R.; Hanna, L. E.; Greene, M. A.; Moore, C. E.; Jarvo, E. R., *J. Am. Chem. Soc.* **2013**, *135*, 3303.
146. Wisniewska, H. M.; Swift, E. C.; Jarvo, E. R., *J. Am. Chem. Soc.* **2013**, *135*, 9083.

147. Harris, M. R.; Konev, M. O.; Jarvo, E. R., *J. Am. Chem. Soc.* **2014**, *136*, 7825.
148. Tollefson, E. J.; Dawson, D. D.; Osborne, C. A.; Jarvo, E. R., *J. Am. Chem. Soc.* **2014**, *136*, 14951.
149. Yonova, I. M.; Johnson, A. G.; Osborne, C. A.; Moore, C. E.; Morrissette, N. S.; Jarvo, E. R., *Angew. Chem. Int. Ed.* **2014**, *53*, 2422.
150. Dawson, D. D.; Jarvo, E. R., *Org. Process Res. Dev.* **2015**, *19*, 1356.
151. Tollefson, E. J.; Erickson, L. W.; Jarvo, E. R., *J. Am. Chem. Soc.* **2015**, *137*, 9760.
152. Erickson, L. W.; Lucas, E. L.; Tollefson, E. J.; Jarvo, E. R., *J. Am. Chem. Soc.* **2016**, *138*, 14006.
153. Konev, M. O.; Hanna, L. E.; Jarvo, E. R., *Angew. Chem. Int. Ed.* **2016**, *55*, 6730.
154. Dawson, D. D.; Oswald, V. F.; Borovik, A. S.; Jarvo, E. R., *Chem. Eur. J* **2020**, *26*, 3044.
155. Sanford, A. B.; Thane, T. A.; McGinnis, T. M.; Chen, P.-P.; Hong, X.; Jarvo, E. R., *J. Am. Chem. Soc.* **2020**, *142*, 5017.
156. Zhou, Q.; Srinivas, H. D.; Dasgupta, S.; Watson, M. P., *J. Am. Chem. Soc.* **2013**, *135*, 3307.
157. Srinivas, H. D.; Zhou, Q.; Watson, M. P., *Org. Lett.* **2014**, *16*, 3596.
158. Zhou, Q.; Cobb, K. M.; Tan, T.; Watson, M. P., *J. Am. Chem. Soc.* **2016**, *138*, 12057.
159. Zhou, Q.; Srinivas, H. D.; Zhang, S.; Watson, M. P., *J. Am. Chem. Soc.* **2016**, *138*, 11989.
160. Cobb, K. M.; Rabb-Lynch, J. M.; Hoerrner, M. E.; Manders, A.; Zhou, Q.; Watson, M. P., *Org. Lett.* **2017**, *19*, 4355.
161. Xu, J.; Bercher, O. P.; Watson, M. P., *J. Am. Chem. Soc.* **2021**, *143*, 8608.
162. Chen, P.-P.; Lucas, E. L.; Greene, M. A.; Zhang, S.-Q.; Tollefson, E. J.; Erickson, L. W.; Taylor, B. L. H.; Jarvo, E. R.; Hong, X., *J. Am. Chem. Soc.* **2019**, *141*, 5835.
163. Zhang, S.-Q.; Taylor, B. L. H.; Ji, C.-L.; Gao, Y.; Harris, M. R.; Hanna, L. E.; Jarvo, E. R.; Houk, K. N.; Hong, X., *J. Am. Chem. Soc.* **2017**, *139*, 12994.

164. Chen, P.-P.; Zhang, H.; Cheng, B.; Chen, X.; Cheng, F.; Zhang, S.-Q.; Lu, Z.; Meng, F.; Hong, X., *ACS Catal.* **2019**, *9*, 9589.
165. Balakrishnan, V.; Murugesan, V.; Chindan, B.; Rasappan, R., *Org. Lett.* **2021**, *23*, 1333.
166. Murugesan, V.; Balakrishnan, V.; Rasappan, R., *J. Catal.* **2019**, *377*, 293.
167. Zarate, C.; Martin, R., *J. Am. Chem. Soc.* **2014**, *136*, 2236.
168. Zarate, C.; Nakajima, M.; Martin, R., *J. Am. Chem. Soc.* **2017**, *139*, 1191.
169. Somerville, R. J.; Hale, L. V. A.; Gómez-Bengoa, E.; Burés, J.; Martin, R., *J. Am. Chem. Soc.* **2018**, *140*, 8771.
170. Hari Babu, M.; Ranjith Kumar, G.; Kant, R.; Sridhar Reddy, M., *Chem. Commun.* **2017**, *53*, 3894.
171. Rajesh, M.; Singam, M. K. R.; Puri, S.; Balasubramanian, S.; Sridhar Reddy, M., *J. Org. Chem.* **2018**, *83*, 15361.
172. Ranjith Kumar, G.; Kumar, R.; Rajesh, M.; Sridhar Reddy, M., *Chem. Commun.* **2018**, *54*, 759.
173. Hanna, L. E.; Konev, M. O.; Jarvo, E. R., *Eur. J. Org. Chem.* **2019**, 184.
174. Shao, X. B.; Zhang, Z.; Li, Q. H.; Zhao, Z. G., *Org. Biomol. Chem.* **2018**, *16*, 4797.
175. Zhou, Z.-Z.; Song, X.-R.; Du, S.; Xia, K.-J.; Tian, W.-F.; Xiao, Q.; Liang, Y.-M., *Chem. Commun.* **2021**, *57*, 9390.

Chapter 2

Cu-Catalyzed Synthesis of Tetrasubstituted 2,3-Allenols through Decarboxylative Silylation of Alkyne-Substituted Cyclic Carbonates



This chapter has been published in:

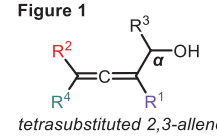
Guo, K.; Kleij, A. W. *Org. Lett.* **2020**, *22*, 3942-3945.

2.1 Introduction

Allenes and their derivatives play an important role in organic synthesis constituting reactive intermediates *en route* to more complex structures,[1] and medicinally useful intermediates.[2] The synthesis of allenes has rapidly advanced over the last decade and various efficient protocols for tri-[3] and tetra-substituted[4] scaffolds have been developed. Silylated congeners have been frequently targeted as these scaffolds can offer productive ways towards pharmaceutically relevant molecules and natural products if properly equipped with additional functionality. In this context, various groups have reported on efficient catalytic silylation protocols using either a wide range of propargylic precursors,[5] (*Z*)-2-alken-4-ynoates[6] and enynes.[7]

The sub-category of 2,3-allenols (Figure 1) are attractive as building blocks for organic synthesis,[8] and have additionally successfully been probed in the construction of natural products.[9] These important 2,3-allenol precursors can be conveniently prepared from alkynyl epoxides as demonstrated previously by various groups[10] but despite progress in this area, a general catalytic protocol that can further advance the access to a wider diversity of functional tetra-substituted 2,3-allenols remains much desired.

Figure 1

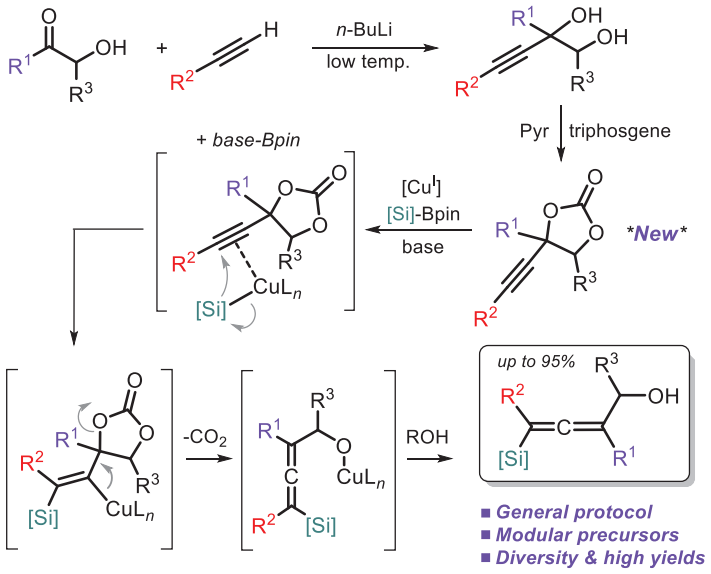


tetrasubstituted 2,3-allenols

2.2 Project Aims and Strategy

Inspired by this synthetic challenge, we set out to explore a new approach towards the preparation of tetra-substituted silylated allenes. In our approach, we used a newly developed substrate based on a cyclic organic carbonate skeleton (Scheme 1) representing a propargylic surrogate.[11] Functional cyclic carbonates such as vinyl-[12] and terminal alkyne-substituted ones[13] have recently emerged as highly versatile, modular and readily prepared compounds for the development of elusive C-H bond functionalization and allylic/propargylic substitution reactions. Our new substrate design takes advantage over the accessibility of both *α*-hydroxy ketones and terminal alkynes, and their coupling mediated by *n*-butyl lithium affords key *syn*-diols which are easily converted into the

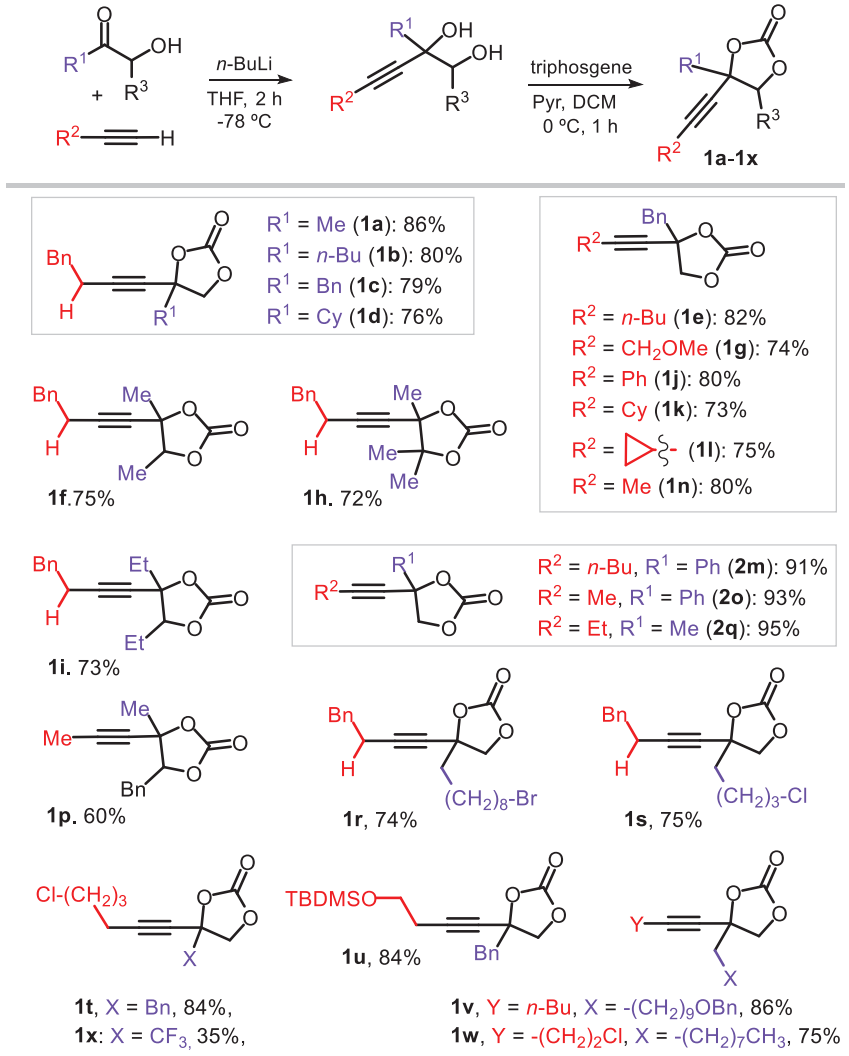
requisite alkynyl carbonate substrates. Formation of a π-complex in the presence of a Cu(I) species should lead to decarboxylative nucleophilic functionalization of the alkyne carbonate by the activated silyl reagent and affording the targeted tetrasubstituted allene product.



Scheme 1. Copper-mediated formation of tetra-substituted silylated 2,3-allenols using newly designed alkynyl-derived cyclic carbonates.

This envisioned manifold proceeds through a *syn*-selective 1,2-addition across the C≡C bond followed by an *anti*-selective β-elimination,[5a] triggering the extrusion of a non-charged leaving group (CO_2). The major advantage of using this type of alkynyl carbonates is the highly diverse nature of its precursors enabling to forge a wide range of 2,3-allenols as demonstrated in this chapter.

2.2 Results and discussion

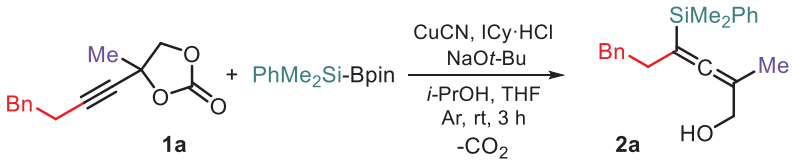


Deviations from the first step of the standard protocol: for compounds **1n-1p**, Me-C≡C-MgBr was used. For **1q**, the reaction conditions are: 2-methyl-1-hexen-3-yne (1 equiv), $K_3Fe(CN)_6$ (3 equiv), K_2CO_3 (3 equiv), quinuclidine (15 mol%), $K_2OsO_2(OH)_4$ (5 mol%), methane sulfonamide (1 equiv), *t*-BuOH/H_2O (1:1 v/v), 48 h, rt; see reference 14. For compound **1x**, see the Experimental Section for details and references 14.

Scheme 2. Two-step synthesis of alkynyl cyclic carbonates **1a-1x** using α-hydroxy ketones and terminal alkynes as reagents.

First, the requisite alkynyl cyclic carbonates (Scheme 2, **1a-1x**) were prepared using a general protocol utilizing *α*-hydroxy ketones and terminal alkynes as easily accessible starting reagents in most cases (*with some exceptions noted*). The yields for most of carbonate substrates in this two-step sequence were appreciably high and typically in the range 70–85% using a standard protocol while for **1n-p**, **1q** and **1x** adapted methods were used.[14] The R-groups present in the carbonate products show ample diversity in terms of positional variation and functionality, with compounds **1r-1x** being exemplary. All carbonate compounds were fully characterized by spectroscopic techniques (see the Experimental Section), and in the case of **1j** also by single crystal X-ray analysis.[15]

Table 1. Optimization of the synthesis of 2,3-allenol **2a** from cyclic carbonate **1a** under Cu-catalysis.[a]

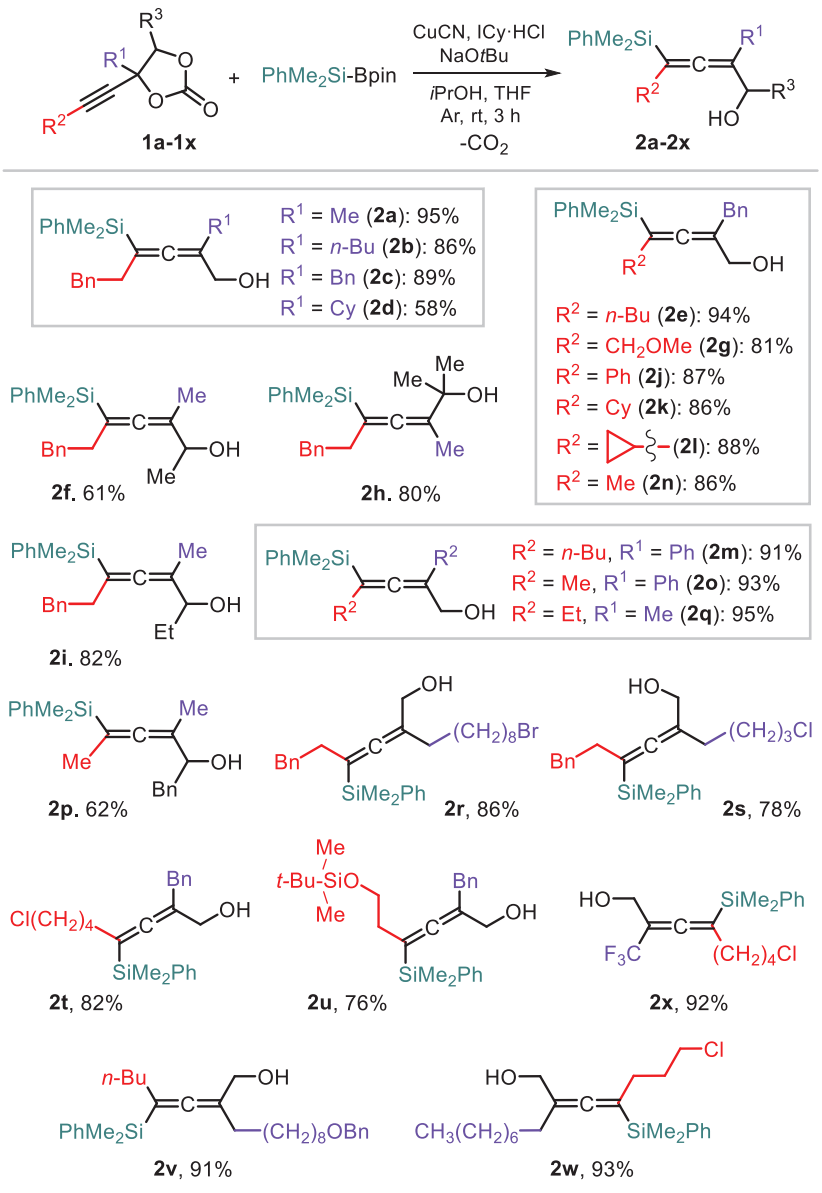


entry	variation from best conditions	yield of **2a** (%)[b]
1	none	95[c]
2	without Cu salt	11
3	without ligand	41
4	without NaO*t*-Bu	<1
5	without *i*-PrOH, and anhydrous	99
6	1.25 equiv of $PhMe_2Si$-Bpin	50

[a]**1a** (0.20 mmol), $PhMe_2Si$-BPin (0.38 mmol), CuCN (5.0 mol%), ICy·HCl (5.0 mol%), NaO*t*-Bu (25 mol%), *i*-PrOH (2.5 equiv), THF (0.20 M), Ar, rt, 3 h. [b]NMR yield ($CDCl_3$) of **2a** with toluene as internal standard. [c]Isolated yield.

With this set of 24 alkynyl cyclic carbonates prepared, we then first screened some reaction conditions to optimize the synthesis of 2,3-allenol **2a** (Table 1).[16] Productive conversion of **1a** into **2a** was accomplished using a combination of CuCN/ICy·HCl (ICy·HCl stands for the carbene ligand 1,3-dicyclohexylimidazolium chloride) in the presence of NaO*t*-Bu as base and THF/*i*-PrOH as medium (entry 1) providing the product in 95% isolated yield. In the absence of the Cu precursor or supporting ligand (ICy·HCl), much lower efficiency was noted (entries 2 and 3). The presence of the base was crucial as no conversion was observed in its absence (entry 4). In the absence of any proton source, nearly quantitative NMR yield of the precursor **2a** was achieved but requiring extensive drying of all reagents and solvents. Finally, the appropriate amount of silylating reagent ($PhMe_2Si$-BPin) was also crucial. If $PhMe_2Si$-BPin was used in larger excess than 1.9 equiv, it was highly difficult to purify the final product. On the contrary, if it was lowered to 1.25 equiv (entry 1 *vs* 6), the yield of **2a** substantially was reduced to a moderate 50%. Combining all observations and for practical reasons, we selected the conditions reported in entry 1 for the product scope phase (Scheme 3: 2,3-allenol compounds **2a**-**2x**).

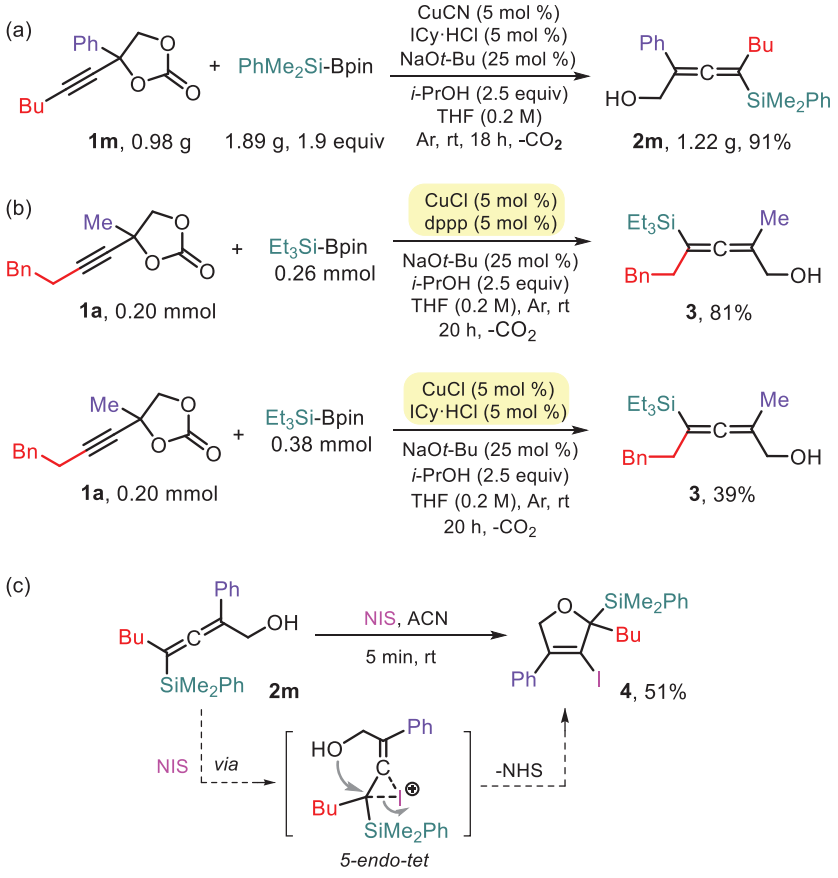
The devised protocol proved to be rather general allowing the introduction of various substituents (R^1, R^2 and R^3) in the allene targets. The presence of simple aryl, benzyl and alkyl substituents are well-tolerated in this Cu-mediated synthesis providing a diverse range of 2,3-allenol compounds (**2a**-**2q**) in typical high isolated yields of up to 95%. Selective C–O bond cleavage in the carbonate **1g** (rather than cleavage of the O–Me group) takes place upon formation of **2g**, whereas the cyclopropyl fragment in **2l** was also not affected. From the observed highs yield of most of the 2,3-allenols it can be assumed that electronic effects exerted by R^1-R^3 play a negligible role, and further variation within the aromatic substituents should allow to amplify the scope of these silylated allenes. Notably, more bulky carbonate precursors with various substituents α to the alcohol group were endorsed, including alkyl (**2f** and **2i**), double alkyl (**2h**) and benzyl (**2p**) groups.



Scheme 3. Preparation of 2,3-allenols **2a-2x** from alkynyl cyclic carbonates **1a-1x**.

In addition, the new silylation methodology also allows the incorporation of several functional groups including alkyl halides (**2r-2t**, **2w** and **2x**) and a protected alcohol (**2u**)

providing further post-synthetic potential. The preparation of allene product **2x** having a CF_3 group provides an alternative route to the one recently reported by Xu and coworkers, who developed Cu-catalyzed 1,4-protosilylation of CF_3-substituted conjugated enynes affording homoallenylsilanes instead of a silyl 2,3-allenol.[7]



Scheme 4. Scale up of **2m** and additional experiments.

In order to examine the practicality of the catalytic formation of these tetra-substituted allenes, we carried out various additional experiments (Scheme 4). Scale up of the preparation of allene product **2m** to gram quantities (Scheme 4a) is feasible, which allows exploring further elaborations. The use of a different silylating reagent ($Et_3SiBPin$) was

then considered to potentially amplify the silyl group diversity in the 2,3-allenol compounds (Scheme 4b). Notably, the high yield synthesis of **3** (81%) using CuCl/dppp as catalyst (dppp = 1,3-diphenylphosphino propane) could be realized under fairly similar reaction conditions compared to the standard protocol.[17] Interestingly, when switching the ligand from dppp to ICy·HCl under the same conditions only provided 39% of the same 2,3-allenol product. This clearly shows the delicate balance between the reactivity of the silyl substrate and the influence of the ligand on the efficiency of the catalytic transformation. Finally, **2m** was used as starting material to investigate its suitability to undergo a formal *5-endo-tet* cyclization after initial iodination (Scheme 4c).[9f] This afforded the dihydrofuran derivative **4** in 51% yield while retaining the initial silyl functionality.

2.4 Conclusion

In summary, novel alkynyl cyclic carbonates have been successfully prepared from simple and cheap starting materials and possess a modular character and represent versatile propargylic surrogates. The utilization of these alkynyl carbonate substrates allowed to devise a diverse scope of tetrasubstituted 2,3-allenols through a Cu-mediated silylation protocol that is characterized by good yields and attractive reaction conditions.

2.5 Experimental Section

2.5.1 General information

Air and water-sensitive reactions were carried out in heat-gun-dried glassware under an Ar or N_2 atmosphere using standard Schlenk techniques. Reactions were monitored by TLC, ^{1}H NMR or GC-FID. TLC was carried out on 0.25 mm Merck aluminum backed sheets coated with 60 F254 silica gel. Visualization of the silica plates was achieved using a UV lamp (λ = 254 nm) and/or by heating plates that were dipped in $KMnO_4$ or ceric ammonium molybdate based stains. Flash chromatography was carried out on Sigma-Aldrich silica gel 60 (70-230 mesh) using the indicated eluent system.

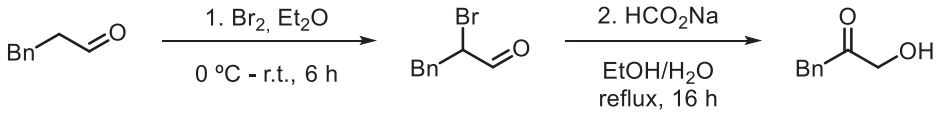
Commercially available reagents and solvents were purchased from Sigma-Aldrich, TCI, Strem Chemicals, ABCR GmbH, Acros Organics or Alfa Aesar and were used without further purification. Solvents were dried using an Innovative Technology PURE SOLV solvent purification system.

^{1}H NMR, ^{13}C NMR, DEPT-90, DEPT-135, and related 2D NMR (gCOSY90, gHMQC, gHMBC, gNOESY) spectra were recorded at room temperature on a Bruker AV-300, AV-400 or AV-500 spectrometer and referenced to their residual deuterated solvent signals. Coupling constants (J) are reported in Hertz with the following splitting abbreviations: s = singlet, d = doublet, t = triplet, q = quadruplet, quint = quintet, sextet = sext, br = broad and app = apparent. All reported NMR values are given in parts per million (ppm). FT-IR measurements were carried out on a Bruker Optics FTIR Alpha spectrometer. Optical rotations were measured with a Jasco P-1030 Polarimeter. Circular dichroism spectrums (CD) were measured on a Chirascan instrument. Mass spectrometric, UPC2, and X-ray analyses were performed by the Research Support Area at ICIQ.

2.5.2 Preparation of α-hydroxy ketones

Hydroxy acetone, acetoin, 3-hydroxy-3-methyl-2-butanone, 4-hydroxy-3-hexanone, and α-hydroxyacetophenone are commercially available reagents and were used without further purification. 1-Hydroxy-4-phenyl-2-butanone, 1-cyclohexyl-2-hydroxyethanone, 3-hydroxy-4-phenyl-2-butanone, and 1-hydroxy-2-undecanone were synthesized following the **General Procedure A**. 1-Hydroxy-2-octanone, 11-bromo-1-hydroxy-2-undecanone, 11-(benzyloxy)-1- hydroxy-2-undecanone, and 6-chloro-1-hydroxy-2-hexanone were synthesized following the **General Procedure B**.

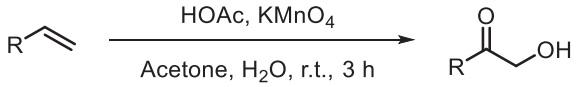
General Procedure A:[18]



Step 1: Bromine (1.02 mL, 1.0 equiv) was added dropwise to a solution of the ketone (20 mmol, 1.0 equiv) in Et_2O (20 mL) at 0 ºC. Then the room solution was stirred for 6 h (until the color of the solution changed from red to light-yellow) at temperature. The reaction progress was monitored by TLC. When the starting material had disappeared, the reaction was quenched with ice water (20 mL) and extracted with Et_2O (3 × 20 mL). The combined organic phases were washed with saturated aqueous $NaHCO_3$ solution (40 mL), brine (40 mL), and dried over Na_2SO_4. After being filtered and concentrated, the residue was used for the next step without further purification. (*Note*: the resulting *α*-bromoketones were used as soon as possible in the next step because they tended to decompose over time at room temperature.)

Step 2: In a round-bottomed flask, the corresponding *α*-bromoketones (20 mmol, 1.0 equiv) was dissolved in EtOH (50 mL) under N_2. A solution of $NaHCO_3$ (8.16 g, 6.0 equiv) in H_2O (10 mL) was added and the mixture was stirred at reflux for 16 h. The mixture was then concentrated in *vacuo*, diluted with H_2O and extracted with EtOAc (3 × 20 mL). The combined organic layers were washed with brine (40 mL), dried over Na_2SO_4, filtered, and concentrated in *vacuo*. The crude product was purified by flash chromatography on silica gel to afford the corresponding *α*-hydroxy ketones.

General Procedure B:[19]

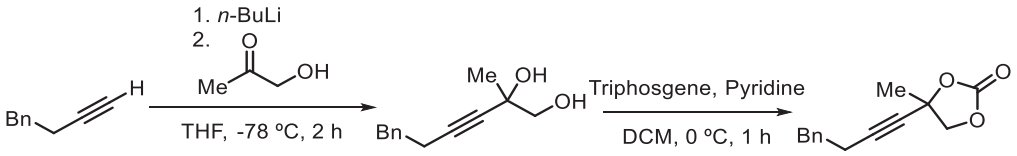


A solution of $KMnO_4$ (5.06 g, 1.6 equiv) in acetone (50 mL) and deionized water (20 mL) was added to the mixture of alkenes (20 mmol, 1.0 equiv), acetone (150 mL), deionized water (50 mL) and glacial acetic acid (8.0 mL). The reaction mixture was stirred at 25 ºC for 3 h. The mixture was then concentrated in *vacuo*. Saturated aqueous $NaHCO_3$ (200 mL) was poured into the reaction mixture and extracted with DCM (3 × 150 mL). The combined organic layer was washed with brine (2 × 100 mL), dried over Na_2SO_4, and concentrated in *vacuo*. The resulting residue was purified by column chromatography on silica gel to give the corresponding *α*-hydroxy ketones.

IMPORTANT NOTE: most of the *α-hydroxy* ketones are rather instable and were used directly to preserve a successful conversion into their respective *syn*-diols.

2.5.3 Synthesis of alkyne-substituted cyclic carbonates 1a-1x.

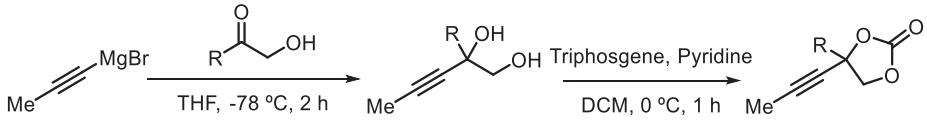
General Procedure C:[13b]



Step 1: To a solution of the alkyne (2.2 equiv) in THF (0.4 M) was added dropwise *n*-BuLi (2.5 M in hexane, 2.2 equiv) at -78 ºC. After the mixture had been stirred for 30 min at the same temperature, the appropriate α-hydroxy carbonyl compound (1.0 equiv) was added. The reaction mixture was allowed to reach room temperature over 30 min. Upon complete consumption of the carbonyl compound, the reaction was quenched with saturated aqueous NH_4Cl. The organic materials were extracted with EtOAc, and the combined organic extracts were washed with brine, dried over Na_2SO_4, and evaporated in *vacuo*. The crude product was dried under high vacuum and used in the next step without further purification.

Step 2: To the diol intermediate (1.0 equiv) in DCM (0.25 M) in an argon flashed flask cooled by an ice bath was added pyridine (4.0 equiv). A solution of triphosgene (0.5 equiv) in DCM (0.25 M) was added and the reaction mixture was allowed to stir for 1 h and followed by TLC. The reaction was quenched with saturated aqueous NH_4Cl and diluted with water. The layers were separated, and the aqueous phase was extracted with DCM three times. The combined organic layers were washed with 1 M HCl (three times), saturated aqueous Na_2CO_3 and brine. After separation, the organic layer was dried over Na_2SO_4, filtered and concentrated in *vacuo*. The crude product was purified by flash chromatography on silica gel to afford the corresponding cyclic carbonate (*reported yields are based on the two-step sequence*).

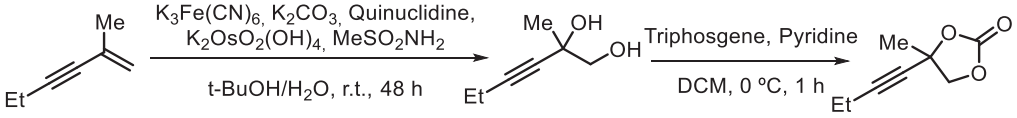
General Procedure D:[20]



Step 1: To a solution of the appropriate *α*-hydroxy carbonyl compound (1.0 equiv) in THF (0.2 M) was added dropwise 1-propynylmagnesium bromide solution (0.5 M in THF, 2.0 equiv) at -78 ºC. After the mixture had been stirred for 30 min at the same temperature, the reaction mixture was allowed to reach room temperature. Upon complete consumption of the carbonyl compound, the reaction was quenched with saturated aqueous NH_4Cl. The organic materials were extracted with EtOAc, and the combined organic extracts were washed with brine, dried over Na_2SO_4, and evaporated in *vacuo*. The crude product was dried under high vacuum and used in the next step without further purification.

Step 2: To the diol intermediate (1.0 equiv) in DCM (0.25 M) in an argon flashed flask cooled by an ice bath was added pyridine (4.0 equiv). A solution of triphosgene (0.5 equiv) in DCM (0.25 M) was added and the reaction was allowed to stir for 1 h and completion checked by TLC. The reaction was quenched with saturated aqueous NH_4Cl and diluted with water. The layers were separated, and the aqueous phase was extracted three times with DCM. The combined organic layers were washed with 1 M HCl (three times), saturated aqueous Na_2CO_3 and brine. After separation, the combined organic layer was dried with Na_2SO_4, filtered and concentrated in *vacuo*. The crude product was purified by flash chromatography on silica gel to afford the corresponding cyclic carbonate (*reported yields are based on the two-step sequence*).

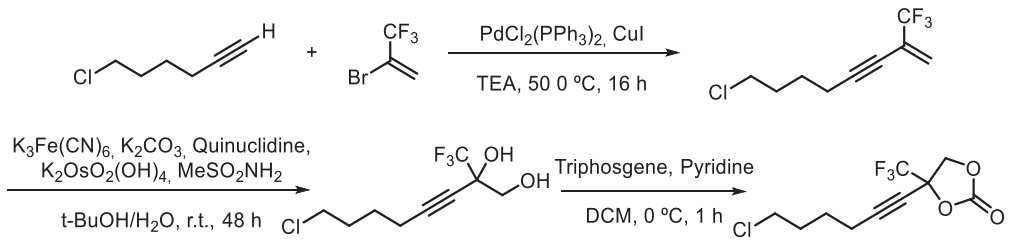
General Procedure E:[14]



Step 1: 2-Methyl-1-hexen-3-yne (1.24 mL, 10 mmol, 1.0 equiv) and $K_3Fe(CN)_6$ (9.8 g, 3.0 equiv.), K_2CO_3 (4.1 g, 3.0 equiv.), quinuclidine (178 mg, 15 mol %), $K_2OsO_2(OH)_4$ (180 mg, 5 mol %) and methane sulfonamide (928 mg, 1.0 equiv) were suspended in *t*-BuOH/H_2O (50 mL each) and the mixture was stirred at room temperature for 48 h. Na_2SO_3 (15 g) was added, the mixture was extracted with EtOAc, and the combined organic layers were dried over Na_2SO_4 and concentrated under reduced pressure. The crude was purified by flash column chromatography over silica gel affording the pure compounds as colorless oils.

Step 2: To the diol intermediate (1.0 equiv) in DCM (0.25 M) in an argon flashed flask cooled by an ice bath was added pyridine (4.0 equiv). A solution of triphosgene (0.5 equiv.) in DCM (0.25 M) was added and the reaction mixture was allowed to stir for 1 h and checked by TLC. The reaction mixture was quenched with saturated aqueous NH_4Cl and diluted with water. The layers were separated, and the aqueous phase was extracted three times with DCM. The combined organic layers were washed with 1 M HCl (three times), saturated aqueous Na_2CO_3 and brine. After separation, the organic layers were dried over Na_2SO_4, filtered and concentrated *in vacuo*. The crude product was purified by flash chromatography on silica gel to afford the corresponding cyclic carbonate (*reported yields are based on a two-step sequence*).

General Procedure F:[14, 7]



Step 1: Under argon atmosphere, $PdCl_2(PPh_3)_2$ (0.14 g, 2 mol %) and CuI (0.10 g, 5 mol %) were added into an oven-dried Schlenk flask, followed by dry degassed triethylamine (30 mL) and 2-bromo-3,3,3-trifluoroprop-1-ene (1.75 g, 10 mmol, 1.0 equiv.). The corresponding terminal alkyne (11 mmol, 1.1 equiv.) was added dropwise via a syringe. The slurry was stirred at 50 ºC (oil bath) overnight, and then quenched with a saturated NH_4Cl solution, extracted with hexane, and dried over anhydrous Na_2SO_4. After concentration under vacuum, the residue was purified by column chromatography over silica gel using hexanes as eluent.

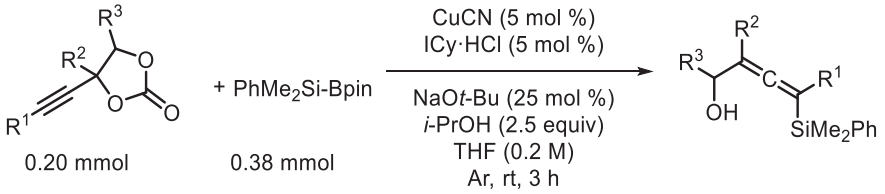
Step 2: The enyne intermediate (1.0 equiv) and $K_3Fe(CN)_6$ (3.0 equiv), K_2CO_3 (3.0 equiv), quinuclidine (15 mol %), $K_2OsO_2(OH)_4$ (5 mol %) and methane sulfonamide (1.0 equiv) were suspended in *t*-BuOH/H_2O (50 mL each) and the mixture stirred at room temperature for 48 h. Na_2SO_3 (15 g) was added, the mixture was extracted with EtOAc, the combined organic layers were dried over Na_2SO_4 and concentrated under reduced pressure. The crude was purified by flash column chromatography over silica gel affording the pure compound as a colorless oil.

Step 3: To the diol intermediate (1.0 equiv) in DCM (0.25 M) in an argon flashed flask cooled by an ice bath was added pyridine (4.0 equiv). A solution of triphosgene (0.5 equiv) in DCM (0.25 M) was added and the reaction mixture was allowed to stir for 1 h and checked by TLC. The reaction mixture was quenched with saturated aqueous NH_4Cl and diluted with water. The layers were separated, and the aqueous phase was extracted three times with DCM. The combined organic layers were washed with 1 M HCl (three times),

saturated aqueous Na_2CO_3 and brine. After separation, the organic layers were dried over Na_2SO_4, filtered and concentrated *in vacuo*. The crude product was purified by flash chromatography on silica gel to afford the corresponding cyclic carbonate (*reported yields are based on a two-step sequence*).

2.5.4 Preparation of and analysis data for 2,3-allenols 2a-2x.

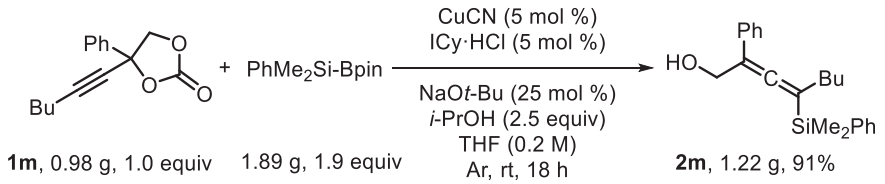
General Procedure G:



In a N_2-filled glove box, a pre-dried 2 mL vial was charged with the cyclic carbonate (1.0 equiv), $PhMe_2Si$-Bpin (1.9 equiv), NaO*t*-Bu (25 mol %), ICy·HCl (5 mol %), CuCN (5 mol %), *i*-PrOH (2.5 equiv), and THF (0.2 M). The reaction mixture was stirred for 3 h at room temperature. Hereafter, the solvent was evaporated by a gentle stream of N_2 and the residue was purified by flash chromatography on silica gel to afford the corresponding products as oils.

2.5.5 Scale up reaction

Procedure H:

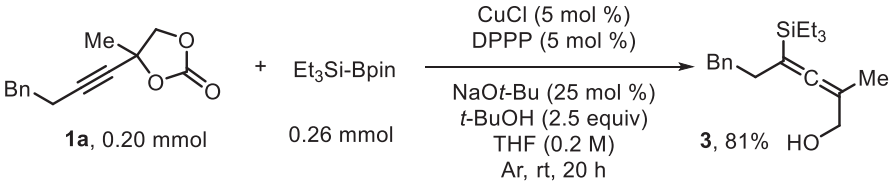


In a N_2-filled glove box, a dried 2 mL vial was charged with the cyclic carbonate **1m** (0.98 g, 1.0 equiv), $PhMe_2Si$-Bpin (1.89 g, 1.9 equiv), NaO*t*-Bu (96.1 mg, 25 mol %), ICy·HCl (53.8 mg, 5 mol %), CuCN (17.9 mg, 5 mol %), *i*-PrOH (0.60 g, 2.5 equiv), and

THF (20 mL). The reaction mixture was stirred for 18 h at room temperature. Hereafter, the solvent was evaporated with a gentle stream of N_2 and the residue purified by flash chromatography (eluent: 1-3 % EtOAc/hexanes) on silica gel to afford the corresponding product **2m** as an oil in 91% yield (1.22 g).

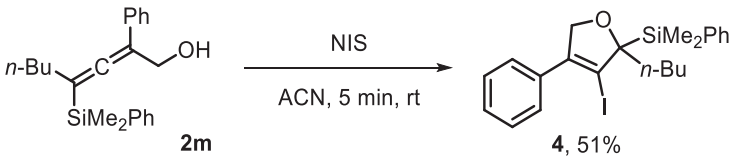
2.5.6 Additional Experiments

General Procedure I:



In a N_2-filled glove box, a dried 2 mL vial was charged with cyclic carbonate **1a** (1.0 equiv), $PhMe_2Si$-Bpin (1.9 equiv), NaO*t*-Bu (25 mol %), DPPP (5 mol %), CuCl (5 mol %), *i*-PrOH (2.5 equiv), and THF (0.2 M). The reaction mixture was stirred for 3 h at room temperature. Hereafter, the solvent was evaporated with a gentle stream of N_2 and the residue purified by flash chromatography on silica gel (eluent 1-3% EtOAc/hexanes) to afford the corresponding product **3** as an oil.

General Procedure J:[9f]

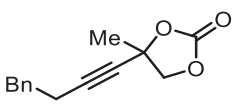


The 2,3-allenol **2m** (0.2 mmol, 1 equiv) was dissolved in acetonitrile (0.1 M) and then *N*-iodosuccinimide (0.24 mol, 1.2 equiv) was added. After 5 minutes of stirring at room temperature , TLC showed complete conversion of the substrate and the reaction mixture was quenched with 2 mL of a saturated solution of $Na_2S_2O_3$. After two extractions with ethyl acetate, the combined organic layers were washed with a saturated solution of sodium

chloride, dried over Na_2SO_4, filtered and concentrated under reduced pressure to afford the crude product which was then purified by flash chromatography (eluent 1% EtOAc/hexanes) to obtain the desired product **4** as an oil.

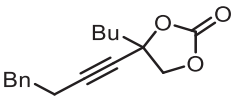
2.5.7 Analytical data for carbonate compounds 1a-1x:

4-methyl-4-(4-phenylbut-1-yn-1-yl)-1,3-dioxolan-2-one (**1a**)



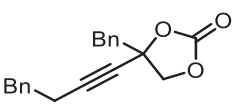
Following the General Procedure C. Yellowish oil (1.98 g, 86% yield). Eluent 5-10% EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.36 – 7.28 (m, 2H), 7.25 – 7.17 (m, 3H), 4.38 (d, *J* = 8.2 Hz, 1H), 4.16 (d, *J* = 8.2 Hz, 1H), 2.83 (t, *J* = 7.4 Hz, 2H), 2.53 (t, *J* = 7.4 Hz, 2H), 1.69 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 153.8, 139.9, 128.5, 126.6, 88.6, 78.3, 76.0, 75.6, 34.4, 26.8, 20.8. **HRMS** (ESI/TOF) *m/z***:** $[M + Na]^+$ Calcd for $C_{14}H_{14}NaO_3$ 253.0844; Found 253.0835.

4-butyl-4-(4-phenylbut-1-yn-1-yl)-1,3-dioxolan-2-one (**1b**)



Following the General Procedure C. Yellowish oil (2.17 g, 80% yield). Eluent 5-10% EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.30 (m, *J* = 6.8, 2H), 7.25 – 7.17 (m, 3H), 4.34 (d, *J* = 8.2 Hz, 1H), 4.17 (d, *J* = 8.2 Hz, 1H), 2.83 (t, *J* = 7.3 Hz, 2H), 2.56 (t, *J* = 7.3 Hz, 2H), 1.87 (m, 1H), 1.81 – 1.72 (m, 1H), 1.45 (m, 1H), 1.40 – 1.30 (m, 3H), 0.91 (t, *J* = 7.1 Hz, 1H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.0, 139.9, 128.5, 126.5, 89.3, 79.3, 77.6, 74.7, 39.4, 34.4, 25.8, 22.4, 20.8, 13.8. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{17}H_{20}NaO_3$ 295.1305; Found 295.1305.

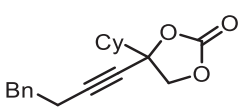
4-benzyl-4-(4-phenylbut-1-yn-1-yl)-1,3-dioxolan-2-one (**1c**)



Following the General Procedure C. Yellowish oil (2.41 g, 79% yield). Eluent 5-10% EtOAc/hexanes. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.36 – 7.28 (m, 5H), 7.25 – 7.20 (m, 3H), 7.18 – 7.15 (m, 2H), 4.31 (d, *J* = 8.3 Hz, 1H), 4.26 (d, *J* = 8.3 Hz, 1H), 3.16 (d, *J* = 1.2 Hz, 2H), 2.81 (t, *J* = 7.4 Hz, 2H), 2.54 (t, *J* = 7.4 Hz, 2H). **^{13}C NMR** (126 MHz, $CDCl_3$) δ 154.0, 140.3, 133.1,

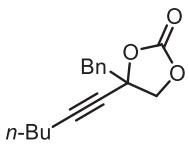
130.9, 129.0, 128.8, 128.8, 128.2, 126.9, 90.8, 78.8, 78.1, 73.6, 45.4, 34.6, 21.2. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{20}H_{18}NaO_3$ 329.1148; Found 329.1148.

4-cyclohexyl-4-(4-phenylbut-1-yn-1-yl)-1,3-dioxolan-2-one (**1d**)



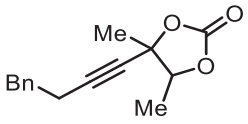
Following the General Procedure C. Yellowish oil (1.13 g, 76% yield). Eluent 5-10% EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.35 – 7.28 (m, 2H), 7.25 – 7.18 (m, 3H), 4.29 (d, *J* = 8.3 Hz, 1H), 4.24 (d, *J* = 8.3 Hz, 1H), 2.84 (t, *J* = 7.3 Hz, 2H), 2.57 (t, *J* = 7.1 Hz, 2H), 1.91 – 1.83 (m, 1H), 1.82 – 1.73 (m, 2H), 1.73 – 1.60 (m, 2H), 1.57 – 1.50 (m, 2H), 1.27 – 1.01 (m, 5H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.1, 139.9, 128.5, 128.4, 126.5, 89.7, 82.3, 76.8, 73.7, 46.1, 34.4, 26.8, 26.6, 25.8, 25.5, 25.4, 20.7. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{19}H_{22}NaO_3$ 321.1461; Found 321.1461.

4-benzyl-4-(hex-1-yn-1-yl)-1,3-dioxolan-2-one (**1e**)



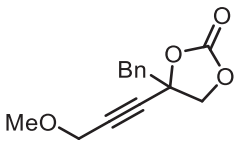
Following the General Procedure C. Yellowish oil (2.11 g, 82% yield). Eluent 5-10% EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.38 – 7.27 (m, 5H), 4.35 (s, 2H), 3.20 (s, 2H), 2.23 (t, *J* = 7.0 Hz, 2H), 1.52 – 1.43 (m, 2H), 1.41 – 1.30 (m, 2H), 0.90 (t, *J* = 7.3 Hz, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 153.7, 132.9, 130.5, 128.6, 127.8, 91.5, 78.7, 76.7, 73.4, 45.2, 30.0, 21.9, 18.3, 13.5. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{16}H_{18}NaO_3$ 281.1158; Found 281.1148.

4,5-dimethyl-4-(4-phenylbut-1-yn-1-yl)-1,3-dioxolan-2-one (**1f**)



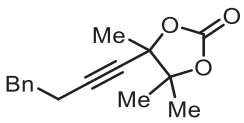
Following the General Procedure C. Yellowish oil (1.83 g, 75% yield). Eluent 5-10% EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.25 – 7.17 (m, 2H), 7.15 – 7.07 (m, 3H), 4.55 (q, *J* = 6.5 Hz, 1H), 2.73 (t, *J* = 7.4 Hz, 2H), 2.43 (t, *J* = 7.4 Hz, 2H), 1.42 (s, 3H), 1.24 (d, *J* = 6.5 Hz, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 153.3, 139.9, 128.5, 128.4, 126.6, 88.5, 81.4, 81.3, 78.8, 78.2, 34.4, 21.7, 20.8, 14.0. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{15}H_{16}NaO_3$ 267.0992; Found 267.0996.

4-benzyl-4-(3-methoxyprop-1-yn-1-yl)-1,3-dioxolan-2-one (**1g**)



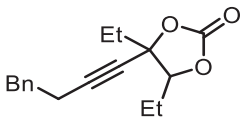
Following the General Procedure C. Yellowish oil (1.82 g, 74% yield). Eluent 5-15% EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.38 – 7.28 (m, 5H), 4.42 (d, *J* = 8.5 Hz, 1H), 4.38 (d, *J* = 8.5 Hz, 1H), 4.14 (s, 2H), 3.33 (s, 3H), 3.25 (d, *J* = 2.2 Hz, 2H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 153.4, 132.4, 130.5, 128.7, 128.1, 86.1, 82.6, 78.1, 73.0, 59.6, 57.9, 44.9. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{14}H_{14}NaO_4$ 269.0784; Found 269.0787.

4,4,5-trimethyl-5-(4-phenylbut-1-yn-1-yl)-1,3-dioxolan-2-one (**1h**)



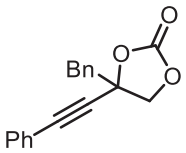
Following the General Procedure C. Yellowish oil (1.85 g, 72% yield). Eluent 5-10% EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.34 – 7.27 (m, 2H), 7.25 – 7.16 (m, 3H), 2.83 (t, *J* = 7.3 Hz, 2H), 2.56 (t, *J* = 7.3 Hz, 2H), 1.57 (s, 3H), 1.43 (s, 3H), 1.37 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 153.2, 140.0, 128.5, 126.5, 89.9, 85.9, 82.4, 76.6, 34.3, 24.2, 23.1, 21.6, 20.7. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{16}H_{18}NaO_3$ 281.1148; Found 281.1148.

4,5-diethyl-4-(4-phenylbut-1-yn-1-yl)-1,3-dioxolan-2-one (**1i**)



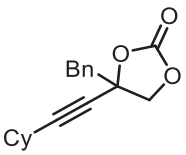
Following the General Procedure C. Yellowish oil (1.99 g, 73% yield). Eluent 5-10% EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.33 – 7.28 (m, 2H), 7.24 – 7.18 (m, 3H), 4.42 (dd, *J* = 9.5, 4.4 Hz, 1H), 2.83 (t, *J* = 7.3 Hz, 2H), 2.56 (t, *J* = 7.3 Hz, 2H), 1.91 – 1.74 (m, 2H), 1.70 – 1.55 (m, 2H), 1.15 – 0.94 (m, 6H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 153.6, 140.0, 128.5, 128.4, 126.5, 89.3, 86.9, 82.4, 77.2, 34.4, 27.6, 21.7, 20.8, 10.3, 8.3. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{17}H_{20}NaO_3$ 295.1305; Found 295.1301.

4-benzyl-4-(phenylethynyl)-1,3-dioxolan-2-one (**1j**)



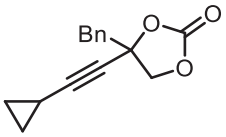
Following the General Procedure C. Yellowish solid (2.22 g, 80% yield). Eluent 5-10% EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.46 – 7.31 (m, 10H), 4.51 (d, *J* = 8.5 Hz, 1H), 4.47 (d, *J* = 8.5 Hz, 1H), 3.34 (d, *J* = 1.1 Hz, 2H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 153.6, 132.7, 131.9, 130.6, 129.6, 128.7, 128.5, 128.0, 120.8, 89.8, 84.8, 78.7, 73.2, 45.2. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{18}H_{14}NaO_3$ 301.0835; Found 301.0836.

4-benzyl-4-(cyclohexylethynyl)-1,3-dioxolan-2-one (**1k**)



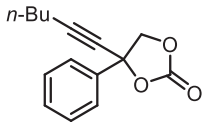
Following the General Procedure C. Yellowish oil (1.65 g, 73% yield). Eluent 5-10% EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.38 – 7.28 (m, 5H), 4.42 – 4.30 (m, 2H), 3.20 (d, *J* = 3.1 Hz, 2H), 2.51 – 2.33 (m, 1H), 1.80 – 1.70 (m, 2H), 1.69 – 1.59 (m, 2H), 1.55 – 1.47 (m, 1H), 1.47 – 1.36 (m, 2H), 1.36 – 1.23 (m, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 153.7, 133.0, 130.6, 128.5, 127.8, 95.3, 78.7, 76.6, 73.5, 45.3, 32.0, 32.0, 29.0, 25.7, 24.6. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{18}H_{20}NaO_3$ 307.1305; Found 307.1303.

4-benzyl-4-(cyclopropylethynyl)-1,3-dioxolan-2-one (**1l**)



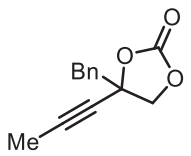
Following the General Procedure C. Yellowish oil (1.81 g, 75% yield). Eluent 5-10% EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.37 – 7.31 (m, 3H), 7.29 – 7.24 (m, 2H), 4.33 (s, 2H), 3.18 (s, 2H), 1.33 – 1.20 (m, 1H), 0.90 – 0.77 (m, 2H), 0.74 – 0.65 (m, 2H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 153.7, 132.9, 130.5, 128.6, 127.9, 94.6, 78.7, 73.2, 71.7, 45.3, 8.5, 8.5, -0.69. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{15}H_{14}NaO_3$ 265.0835; Found 265.0837.

4-(hex-1-yn-1-yl)-4-phenyl-1,3-dioxolan-2-one (**1m**)



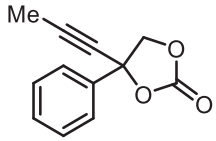
Following the General Procedure C. Yellowish oil (1.83 g, 75% yield). Eluent 5-10% EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.61 – 7.52 (m, 2H), 7.49 – 7.37 (m, 3H), 4.71 (d, *J* = 8.3 Hz, 1H), 4.46 (d, *J* = 8.3 Hz, 1H), 2.33 (t, *J* = 7.1 Hz, 2H), 1.60 – 1.52 (m, 2H), 1.48 – 1.37 (m, 2H), 0.93 (t, *J* = 7.3 Hz, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.0, 137.9, 129.5, 129.0, 125.2, 92.1, 80.0, 77.7, 76.6, 30.1, 22.0, 18.5, 13.5. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{15}H_{16}NaO_3$ 267.0992; Found 267.0986.

4-benzyl-4-(prop-1-yn-1-yl)-1,3-dioxolan-2-one (**1n**)



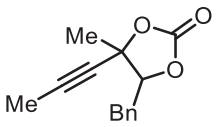
Following the General Procedure D. Yellowish oil (1.73 g, 80% yield). Eluent 5-10% EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.40 – 7.31 (m, 3H), 7.29 (dd, *J* = 7.5, 2.0 Hz, 2H), 4.34 (d, *J* = 0.7 Hz, 2H), 3.20 (s, 1H), 3.20 (s, 1H), 1.89 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 153.7, 132.8, 130.5, 128.6, 127.9, 87.0, 78.5, 76.0, 73.2, 45.1, 3.6. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{13}H_{12}NaO_3$ 239.0679; Found 239.0675.

4-phenyl-4-(prop-1-yn-1-yl)-1,3-dioxolan-2-one (**1o**)



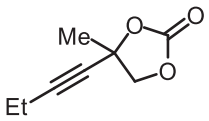
Following the General Procedure D. Yellowish oil (1.72 g, 85% yield). Eluent 5-10% EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.59 – 7.53 (m, 2H), 7.47 – 7.39 (m, 3H), 4.72 (d, *J* = 8.3 Hz, 1H), 4.46 (d, *J* = 8.3 Hz, 1H), 1.98 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 153.9, 137.8, 129.6, 129.0, 125.2, 87.7, 79.9, 77.5, 75.9, 3.8. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{12}H_{10}NaO_3$ 225.0522; Found 225.0520.

5-benzyl-4-methyl-4-(prop-1-yn-1-yl)-1,3-dioxolan-2-one (**1p**)



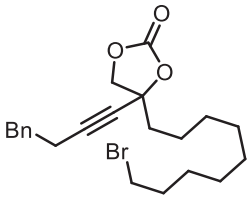
Following the General Procedure D. Yellowish oil (1.38 g, 60% yield). Eluent 5-10% EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.38 – 7.27 (m, 5H), 4.80 (dd, *J* = 9.6, 3.9 Hz, 1H), 3.04 – 2.90 (m, 2H), 1.87 (s, 3H), 1.66 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 153.1, 135.3, 129.1, 128.8, 127.3, 85.6, 85.4, 78.8, 76.2, 35.0, 22.1, 3.6. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{14}H_{14}NaO_3$ 253.0835; Found 253.0838.

4-(but-1-yn-1-yl)-4-methyl-1,3-dioxolan-2-one (**1q**)



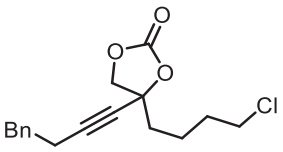
Following the General Procedure E. Colorless oil (1.00 g, 65% yield). Eluent 5-10 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 4.46 (d, *J* = 8.2 Hz, 1H), 4.20 (d, *J* = 8.2 Hz, 1H), 2.24 (q, *J* = 7.5 Hz, 2H), 1.73 (s, 3H), 1.15 (t, *J* = 7.5 Hz, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 153.9, 90.8, 76.7, 76.1, 75.7, 27.0, 13.2, 12.3. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_8H_{10}NaO_3$ 177.0522; Found 177.0526.

4-(9-bromononyl)-4-(4-phenylbut-1-yn-1-yl)-1,3-dioxolan-2-one (**1r**)



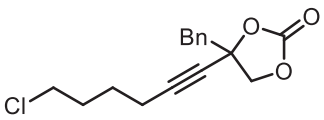
Following the General Procedure C. Yellowish oil (2.48 g, 74% yield). Eluent 5-10% EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.34 – 7.27 (m, 2H), 7.25 – 7.17 (m, 3H), 4.34 (d, *J* = 8.2 Hz, 1H), 4.17 (d, *J* = 8.2 Hz, 1H), 3.41 (t, *J* = 6.8 Hz, 2H), 2.83 (t, *J* = 7.3 Hz, 2H), 2.55 (t, *J* = 7.3 Hz, 2H), 1.92 – 1.81 (m, 3H), 1.81 – 1.72 (m, 1H), 1.50 – 1.36 (m, 4H), 1.36 – 1.22 (m, 8H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.0, 139.9, 128.5, 126.5, 89.4, 79.3, 77.6, 74.7, 39.6, 34.4, 34.0, 32.8, 29.3, 29.2, 29.2, 28.7, 28.1, 23.7, 20.8. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{22}H_{29}BrNaO_3$ 443.1192; Found 443.1196.

4-(4-chlorobutyl)-4-(4-phenylbut-1-yn-1-yl)-1,3-dioxolan-2-one (**1s**)



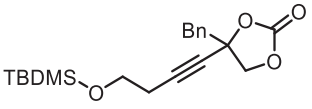
Following the General Procedure C. Yellowish oil (2.29 g, 75% yield). Eluent 5-10% EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.34 – 7.28 (m, 2H), 7.26 – 7.17 (m, 3H), 4.36 (d, *J* = 8.3 Hz, 1H), 4.18 (d, *J* = 8.3 Hz, 1H), 3.52 (t, *J* = 6.5 Hz, 2H), 2.84 (t, *J* = 7.3 Hz, 2H), 2.57 (t, *J* = 7.3 Hz, 2H), 1.95 – 1.72 (m, 4H), 1.69 – 1.51 (m, 2H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 153.8, 139.9, 128.5, 126.6, 89.8, 78.9, 77.2, 74.7, 44.3, 38.8, 34.3, 31.9, 21.3, 20.7. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{17}H_{19}ClNaO_3$ 329.0915; Found 329.0921.

4-benzyl-4-(6-chlorohex-1-yn-1-yl)-1,3-dioxolan-2-one (**1t**)



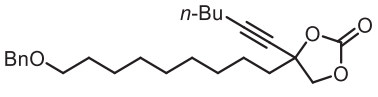
Following the General Procedure C. Yellowish oil (2.45 g, 84% yield). Eluent 5-10% EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.38 – 7.31 (m, 3H), 7.31 – 7.27 (m, 2H), 4.36 (s, 2H), 3.52 (t, *J* = 6.4 Hz, 2H), 3.20 (d, *J* = 2.1 Hz, 2H), 2.28 (t, *J* = 6.9 Hz, 2H), 1.85 – 1.72 (m, 2H), 1.71 – 1.60 (m, 2H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 153.6, 132.9, 130.5, 128.6, 127.9, 90.5, 78.6, 77.3, 73.4, 45.2, 44.3, 31.3, 25.2, 18.0. **HRMS** (ESI/TOF) *m/z:* $[M + Na]^+$ Calcd for $C_{16}H_{17}ClNaO_3$ 315.0758; Found 315.0765.

4-benzyl-4-(4-((*tert*-butyldimethylsilyl)oxy)but-1-yn-1-yl)-1,3-dioxolan-2-one (**1u**)



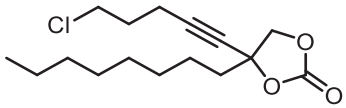
Following the General Procedure C. Yellowish oil (3.02 g, 84% yield). Eluent 5-10% EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.37 – 7.31 (m, 3H), 7.31 – 7.27 (m, 2H), 4.35 (s, 2H), 3.70 (t, *J* = 6.9 Hz, 2H), 3.20 (d, *J* = 3.0 Hz, 2H), 2.45 (t, *J* = 6.9 Hz, 2H), 0.90 (s, 9H), 0.07 (s, 6H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 153.6, 132.8, 130.5, 128.6, 127.9, 88.5, 78.4, 77.8, 73.1, 61.1, 45.1, 25.8, 23.1, 18.3, -5.32. **HRMS** (ESI/TOF) *m/z:* $[M + Na]^+$ Calcd for $C_{20}H_{28}NaO_4Si$ 383.1649; Found 383.1644.

4-(9-(benzyloxy)nonyl)-4-(hex-1-yn-1-yl)-1,3-dioxolan-2-one (**1v**)



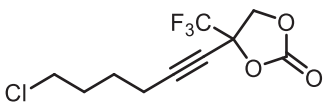
Following the General Procedure C. Yellowish oil (3.44 g, 86% yield). Eluent 5-15% EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.38 – 7.32 (m, 4H), 7.31 – 7.26 (m, 1H), 4.50 (s, 2H), 4.42 (d, *J* = 8.2 Hz, 1H), 4.21 (d, *J* = 8.2 Hz, 1H), 3.46 (t, *J* = 6.6 Hz, 2H), 2.25 (t, *J* = 7.0 Hz, 2H), 1.97 – 1.75 (m, 2H), 1.65 – 1.56 (m, 2H), 1.56 – 1.46 (m, 2H), 1.46 – 1.21 (m, 14H), 0.92 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.0, 138.7, 128.3, 127.6, 127.5, 90.4, 79.4, 76.6, 74.8, 72.9, 70.5, 39.8, 30.2, 29.8, 29.4, 29.4, 29.3, 29.2, 26.2, 23.8, 21.9, 18.3, 13.5. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{25}H_{36}NaO_4$ 423.2506; Found 423.2509.

4-(5-chloropent-1-yn-1-yl)-4-octyl-1,3-dioxolan-2-one (**1w**)



Following the General Procedure C. Yellowish oil (1.80 g, 75% yield). Eluent 5-10% EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 4.43 (d, *J* = 8.3 Hz, 1H), 4.23 (d, *J* = 8.2 Hz, 1H), 3.62 (t, *J* = 6.2 Hz, 2H), 2.47 (t, *J* = 6.9 Hz, 2H), 2.06 – 1.94 (m, 2H), 1.93 – 1.79 (m, 2H), 1.54 – 1.43 (m, 1H), 1.40 – 1.21 (m, 10H), 0.97 – 0.82 (m, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 153.9, 88.2, 79.2, 77.7, 74.7, 43.3, 39.7, 31.8, 30.8, 29.3, 29.2, 29.1, 23.8, 22.6, 16.1, 14.1. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{16}H_{25}ClNaO_3$ 323.1384; Found 323.1390.

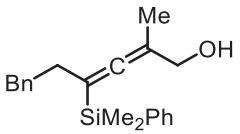
4-(6-chlorohex-1-yn-1-yl)-4-(trifluoromethyl)-1,3-dioxolan-2-one (**1x**)



Following the General Procedure F. Colorless oil (0.94 g, 35% yield). Eluent 5-10 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 4.68 (d, *J* = 9.4 Hz, 1H), 4.51 (dd, *J* = 9.4, 1.1 Hz, 1H), 3.57 (t, *J* = 6.3 Hz, 2H), 2.38 (t, *J* = 7.0 Hz, 2H), 1.94 – 1.82 (m, 2H), 1.80 – 1.71 (m, 2H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 151.7, 123.0, 120.2, 93.6, 75.4, 75.0, 70.0, 70.0, 44.1, 31.3, 24.8, 18.1. **^{19}F NMR** (376 MHz, $CDCl_3$) δ -81.9. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{10}H_{10}ClF_3NaO_3$ 293.0163; Found 293.0175.

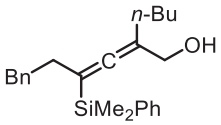
2.5.8 Analysis data for 2,3-allenols 2a-2x, 3 and 4:

4-(dimethyl(phenyl)silyl)-2-methyl-6-phenylhexa-2,3-dien-1-ol (**2a**)



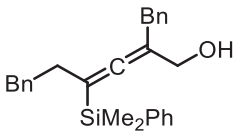
Following the General Procedure G. Colorless oil (61.2 mg, 95% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.59 – 7.51 (m, 2H), 7.44 – 7.35 (m, 3H), 7.32 – 7.24 (m, 2H), 7.22 – 7.17 (m, 1H), 7.16 – 7.11 (m, 2H), 3.92 – 3.80 (m, 2H), 2.78 – 2.70 (m, 2H), 2.37 – 2.29 (m, 2H), 1.64 (s, 3H), 0.40 (s, 6H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 203.9, 142.0, 138.2, 133.8, 129.2, 128.4, 128.2, 127.8, 125.8, 97.4, 96.1, 64.7, 35.2, 30.8, 15.2, -2.9, -3.0. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -7.9. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{21}H_{26}NaOSi$ 345.1645; Found 345.1644.

2-butyl-4-(dimethyl(phenyl)silyl)-6-phenylhexa-2,3-dien-1-ol (**2b**)



Following the General Procedure G. Colorless oil (62.6 mg, 86% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.59 – 7.53 (m, 2H), 7.42 – 7.36 (m, 3H), 7.31 – 7.24 (m, 2H), 7.22 – 7.17 (m, 1H), 7.16 – 7.11 (m, 2H), 3.90 (dd, *J* = 10.5 Hz, 2H), 2.74 (td, *J* = 7.4, 2.2 Hz, 2H), 2.39 – 2.27 (m, 2H), 1.99 – 1.87 (m, 2H), 1.41 – 1.29 (m, 4H), 0.97 – 0.88 (m, 3H), 0.81 (s, 1H), 0.41 (s, 3H), 0.41 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 203.5, 142.1, 138.1, 133.9, 129.2, 128.4, 128.3, 127.8, 125.8, 101.5, 98.7, 63.8, 35.3, 31.0, 30.3, 28.8, 22.7, 14.0, -2.8, -3.0. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.4. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{24}H_{32}NaOSi$ 387.2115; Found 387.2113.

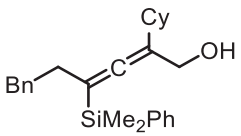
2-benzyl-4-(dimethyl(phenyl)silyl)-6-phenylhexa-2,3-dien-1-ol (**2c**)



Following the General Procedure G. Colorless oil (70.9 mg, 89% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.49 – 7.44 (m, 2H), 7.43 – 7.35 (m, 3H), 7.35 – 7.24 (m, 5H), 7.24 – 7.17 (m, 3H), 7.14 – 7.09 (m, 2H), 4.02 – 3.82 (m, 2H), 3.38 – 3.23 (m, 2H), 2.74 – 2.60 (m, 2H), 2.35 – 2.16 (m, 2H), 0.84 (s, 1H), 0.35 (s, 3H), 0.34 (s, 3H). **^{13}C NMR** (101

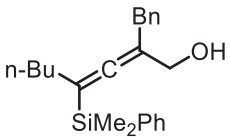
MHz, $CDCl_3$) δ 204.2, 142.1, 139.6, 137.8, 133.9, 129.3, 129.2, 128.4, 128.3, 128.3, 127.8, 126.2, 125.98, 101.3, 98.7, 63.5, 36.1, 35.2, 30.8, -2.9, -3.0. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.1. **HRMS** (ESI/TOF) *m/z:* [M + Na]$^+$ Calcd for $C_{27}H_{30}NaOSi$ 421.1958; Found 421.1951.

2-cyclohexyl-4-(dimethyl(phenyl)silyl)-6-phenylhexa-2,3-dien-1-ol (**2d**)



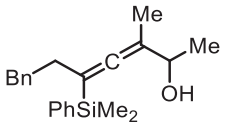
Following the General Procedure G. Colorless oil (45.3 mg, 58% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.58 – 7.51 (m, 2H), 7.42 – 7.34 (m, 3H), 7.30 – 7.23 (m, 2H), 7.21 – 7.15 (m, 1H), 7.14 – 7.09 (m, 2H), 3.99 – 3.81 (m, 2H), 2.72 (t, *J* = 7.7 Hz, 2H), 2.36 – 2.25 (m, 2H), 1.86 – 1.62 (m, 6H), 1.35 – 0.96 (m, 5H), 0.68 (t, *J* = 6.2 Hz, 1H), 0.39 (s, 6H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 203.0, 142.0, 138.1, 133.9, 129.2, 128.4, 128.3, 127.8, 125.8, 107.2, 99.7, 77.4, 77.0, 76.7, 62.6, 37.7, 35.1, 33.0, 32.6, 30.9, 26.6, 26.5, 26.3, -2.8, -3.0. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.8. **HRMS** (ESI/TOF) *m/z***:** [M + Na]$^+$ Calcd for $C_{26}H_{34}NaOSi$ 413.2271; Found 413.2274.

2-benzyl-4-(dimethyl(phenyl)silyl)octa-2,3-dien-1-ol (**2e**)



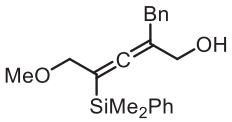
Following the General Procedure G. Colorless oil (65.8 mg, 94% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.48 – 7.43 (m, 2H), 7.40 – 7.35 (m, 3H), 7.32 – 7.26 (m, 2H), 7.25 – 7.21 (m, 1H), 7.21 – 7.17 (m, 2H), 4.06 – 3.94 (m, 2H), 3.40 – 3.27 (m, 2H), 1.98 – 1.88 (m, 2H), 1.39 – 1.22 (m, 4H), 1.04 (s, 1H), 0.87 (t, *J* = 7.2 Hz, 3H), 0.33 (s, 3H), 0.32 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 203.9, 139.6, 138.1, 133.9, 129.2, 129.2, 128.2, 127.8, 126.1, 100.5, 99.4, 63.6, 36.2, 31.5, 29.4, 22.4, 14.0, -2.9, -2.9. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -7.9. **HRMS** (ESI/TOF) *m/z***:** [M + Na]$^+$ Calcd for $C_{23}H_{30}NaOSi$ 373.1958; Found 373.1963.

5-(dimethyl(phenyl)silyl)-3-methyl-7-phenylhepta-3,4-dien-2-ol (**2f**)



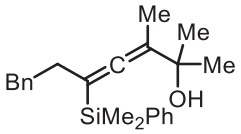
Following the General Procedure G. Colorless oil (41.0 mg, 61% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.57 – 7.49 (m, 2H), 7.41 – 7.35 (m, 3H), 7.29 – 7.24 (m, 2H), 7.21 – 7.16 (m, 1H), 7.15 – 7.10 (m, 2H), 4.12 – 3.90 (m, 1H), 2.77 – 2.65 (m, 2H), 2.38 – 2.24 (m, 2H), 1.62 (s, 3H), 1.17 (d, *J* = 6.4 Hz, 3H), 1.06 – 0.95 (m, 1H), 0.39 (s, 3H), 0.39 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 203.2, 142.1, 138.1, 133.8, 129.2, 128.4, 128.3, 127.8, 125.8, 100.0, 97.6, 69.1, 35.3, 30.9, 21.8, 14.2, -2.8, -3.0. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.0. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{22}H_{28}NaOSi$ 359.1802; Found 359.1800.

2-benzyl-4-(dimethyl(phenyl)silyl)-5-methoxypenta-2,3-dien-1-ol (**2g**)



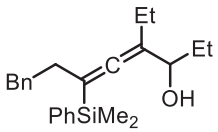
Following the General Procedure G. Colorless oil (54.8 mg, 81% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.49 – 7.44 (m, 2H), 7.40 – 7.34 (m, 3H), 7.31 – 7.25 (m, 2H), 7.24 – 7.14 (m, 3H), 4.04 – 3.94 (m, 3H), 3.87 (d, *J* = 11.7 Hz, 1H), 3.40 – 3.28 (m, 2H), 3.14 (s, 3H), 1.48 (s, 1H), 0.36 (s, 3H), 0.36 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.0, 139.2, 137.8, 133.9, 129.2, 129.2, 128.3, 127.8, 126.2, 100.8, 97.1, 77.4, 77.1, 76.8, 72.2, 63.3, 57.5, 35.8, -2.7, -2.8. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.5. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{21}H_{26}NaO_2Si$ 361.1594; Found 361.1591.

5-(dimethyl(phenyl)silyl)-2,3-dimethyl-7-phenylhepta-3,4-dien-2-ol (**2h**)



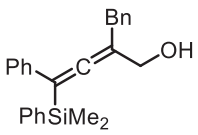
Following the General Procedure G. Colorless oil (56.0 mg, 80% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.58 – 7.51 (m, 2H), 7.42 – 7.36 (m, 3H), 7.30 – 7.24 (m, 2H), 7.21 – 7.11 (m, 3H), 2.73 (t, *J* = 7.8 Hz, 2H), 2.37 – 2.24 (m, 2H), 1.67 (s, 3H), 1.25 (s, 3H), 1.23 (s, 3H), 1.18 (s, 1H), 0.40 (s, 3H), 0.40 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 202.7, 142.2, 138.1, 133.9, 129.2, 128.4, 128.3, 127.8, 125.8, 103.5, 97.6, 77.4, 77.1, 76.8, 70.9, 35.3, 31.0, 28.8, 28.8, 14.2, -2.9, -3.0. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.0. **HRMS** (ESI/TOF) *m/z***:** $[M + Na]^+$ Calcd for $C_{23}H_{30}NaOSi$ 373.1958; Found 373.1958.

6-(dimethyl(phenyl)silyl)-4-ethyl-8-phenylocta-4,5-dien-3-ol (**2i**)



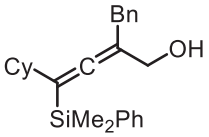
Following the General Procedure G. Colorless oil (59.7 mg, 82% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.60 – 7.53 (m, 2H), 7.43 – 7.36 (m, 3H), 7.30 – 7.24 (m, 2H), 7.23 – 7.17 (m, 1H), 7.16 – 7.10 (m, 2H), 3.89 – 3.77 (m, 1H), 2.81 – 2.67 (m, 2H), 2.41 – 2.25 (m, 2H), 2.05 – 1.87 (m, 2H), 1.65 – 1.52 (m, 1H), 1.51 – 1.40 (m, 1H), 1.04 – 0.98 (m, 4H), 0.95 – 0.89 (m, 3H), 0.42 (s, 3H), 0.42 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 202.9, 142.2, 138.0, 133.9, 129.3, 128.4, 128.3, 127.9, 125.8, 106.4, 100.2, 73.8, 35.5, 31.5, 28.6, 21.2, 12.7, 10.2, -2.7, -2.9. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.3. **HRMS** (ESI/TOF) ***m/z*:** [M + Na]$^{+}$ Calcd for $C_{24}H_{32}NaOSi$ 387.2115; Found 387.2103.

2-benzyl-4-(dimethyl(phenyl)silyl)-4-phenylbuta-2,3-dien-1-ol (**2j**)



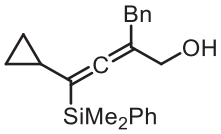
Following the General Procedure G. Colorless oil (64.4 mg, 87% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.56 – 7.47 (m, 2H), 7.45 – 7.35 (m, 3H), 7.32 – 7.13 (m, 10H), 4.19 – 4.07 (m, 2H), 3.53 – 3.37 (m, 2H), 1.22 (s, 1H), 0.45 (s, 3H), 0.43 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 207.1, 139.1, 138.3, 137.1, 134.0, 129.3, 128.4, 128.4, 127.9, 127.8, 126.4, 126.4, 102.1, 101.8, 63.4, 36.0, -1.8, -1.8. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.1. **HRMS** (ESI/TOF) ***m/z*:** [M + Na]$^{+}$ Calcd for $C_{25}H_{26}NaOSi$ 393.1645; Found 393.1656.

2-benzyl-4-cyclohexyl-4-(dimethyl(phenyl)silyl)buta-2,3-dien-1-ol (**2k**)



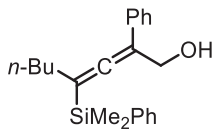
Following the General Procedure G. Colorless oil (64.7 mg, 86% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.49 – 7.43 (m, 2H), 7.40 – 7.34 (m, 3H), 7.32 – 7.26 (m, 2H), 7.25 – 7.21 (m, 1H), 7.21 – 7.16 (m, 2H), 4.02 – 3.91 (m, 2H), 3.37 – 3.25 (m, 2H), 1.86 – 1.75 (m, 1H), 1.73 – 1.54 (m, 5H), 1.24 – 1.02 (m, 4H), 1.00 – 0.87 (m, 2H), 0.33 (s, 6H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 203.8, 139.6, 138.6, 133.9, 129.3, 129.1, 128.2, 127.7, 126.1, 105.5, 101.6, 77.4, 77.1, 76.8, 63.7, 39.0, 36.2, 34.2, 34.2, 26.7, 26.6, 26.1, -2.2, -2.3. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.5. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{25}H_{32}NaOSi$ 399.2115; Found 399.2119.

2-benzyl-4-cyclopropyl-4-(dimethyl(phenyl)silyl)buta-2,3-dien-1-ol (**2l**)



Following the General Procedure G. Colorless oil (58.8 mg, 88% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.52 – 7.46 (m, 2H), 7.43 – 7.34 (m, 3H), 7.31 – 7.25 (m, 2H), 7.24 – 7.19 (m, 1H), 7.16 – 7.10 (m, 2H), 4.06 – 3.87 (m, 2H), 3.36 – 3.18 (m, 2H), 1.11 – 1.05 (m, 1H), 1.04 – 0.98 (m, 1H), 0.62 – 0.53 (m, 2H), 0.36 (s, 3H), 0.36 (s, 3H), 0.35 – 0.30 (m, 1H), 0.12 – 0.04 (m, 1H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 201.6, 139.4, 138.1, 134.0, 133.1, 129.2, 128.3, 127.7, 126.2, 104.1, 103.2, 63.5, 36.1, 10.0, 8.6, 7.5, -2.8, -2.8. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ 7.4. **HRMS** (ESI/TOF) *m/z***:** $[M + Na]^+$ Calcd for $C_{22}H_{26}NaOSi$ 357.1645; Found 357.1644.

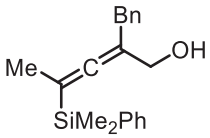
4-(dimethyl(phenyl)silyl)-2-phenylocta-2,3-dien-1-ol (**2m**)



Following the General Procedure G. Colorless oil (61.2 mg, 91% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.60 – 7.55 (m, 2H), 7.44 – 7.31 (m, 7H), 7.23 – 7.18 (m, 1H), 4.53 – 4.46 (m, 2H), 2.21 – 2.07 (m, 2H), 1.54 – 1.42 (m, 2H), 1.39 – 1.28 (m, 2H), 1.19 (d, *J* = 5.2 Hz, 1H), 0.87 (t, *J* = 7.3 Hz, 3H), 0.48 (s, 3H), 0.46 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.0, 137.6, 135.6, 133.8, 129.4, 128.6, 127.9, 126.2, 125.4, 102.3, 101.8, 62.4,

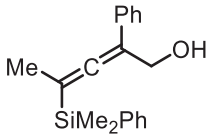
31.6, 29.5, 22.5, 13.9, -2.6, -2.9. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -7.6. **HRMS** (ESI/TOF) ***m/z*:** $[M + Na]^+$ Calcd for $C_{22}H_{28}NaOSi$ 359.1802; Found 359.1802.

2-benzyl-4-(dimethyl(phenyl)silyl)penta-2,3-dien-1-ol (**2n**)



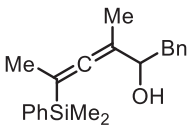
Following the General Procedure G. Colorless oil (53.0 mg, 86% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.45 – 7.40 (m, 2H), 7.40 – 7.33 (m, 3H), 7.32 – 7.26 (m, 2H), 7.25 – 7.21 (m, 1H), 7.21 – 7.16 (m, 2H), 4.09 – 3.93 (m, 2H), 3.33 (q, *J* = 14.9 Hz, 2H), 1.67 (s, 3H), 1.13 (s, 1H), 0.31 (s, 3H), 0.30 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 204.4, 139.6, 137.7, 133.9, 129.2, 129.1, 128.2, 127.8, 126.1, 99.1, 93.8, 63.4, 36.1, 15.9, -3.3, -3.3. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -7.4. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{20}H_{24}NaOSi$ 331.1489; Found 331.1493.

4-(dimethyl(phenyl)silyl)-2-phenylpenta-2,3-dien-1-ol (**2o**)



Following the General Procedure G. Colorless oil (54.7 mg, 93% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.60 – 7.54 (m, 2H), 7.42 – 7.31 (m, 7H), 7.23 – 7.17 (m, 1H), 4.53 – 4.47 (m, 2H), 1.85 (s, 3H), 1.27 (s, 1H), 0.47 (s, 3H), 0.45 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.3, 137.3, 135.5, 133.8, 129.5, 128.6, 128.0, 126.3, 125.6, 100.9, 960, 77.4, 77.1, 76.8, 62.3, 15.6, -3.1, -3.3. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -7.0. **HRMS** (ESI/TOF) ***m/z*:** $[M + Na]^+$ Calcd for $C_{19}H_{22}NaOSi$ 317.1332; Found 317.1333.

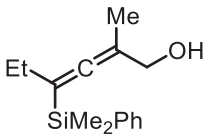
5-(dimethyl(phenyl)silyl)-3-methyl-1-phenylhexa-3,4-dien-2-ol (**2p**)



Following the General Procedure G. Colorless oil (33.9 mg, 62% yield). Eluent 1-3 % EtOAc/hexanes. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.59 – 7.50 (m, 2H), 7.43 – 7.35 (m, 3H), 7.34 – 7.27 (m, 2H), 7.25 – 7.18 (m, 3H), 4.23 – 4.14 (m, 1H), 2.83 (dd, *J* = 13.8, 4.7 Hz, 1H), 2.74 (dd, *J* = 13.8, 7.8 Hz, 1H), 1.73 (s, 3H), 1.61 (s, 3H), 0.37 (s, 3H), 0.36 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 203.9, 138.6, 138.0, 133.8, 129.5, 129.2, 128.3, 127.8, 126.3, 96.4, 93.2, 77.4, 77.1, 76.7, 73.8,

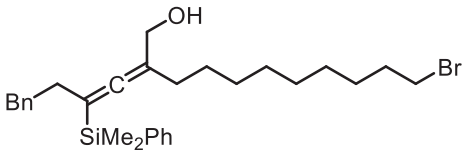
42.2, 15.9, 14. 9, -3.2, -3.3. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -7.7. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{21}H_{26}NaOSi$ 345.1645; Found 345.1655.

4-(dimethyl(phenyl)silyl)-2-methylhexa-2,3-dien-1-ol (**2q**)



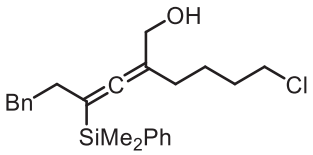
Following the General Procedure G. Colorless oil (46.8 mg, 95% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.58 – 7.48 (m, 2H), 7.42 – 7.34 (m, 3H), 4.00 – 3.90 (m, 2H), 1.99 (q, *J* = 7.3 Hz, 2H), 1.69 (s, 3H), 1.08 (s, 1H), 1.00 (t, *J* = 7.3 Hz, 3H), 0.38 (s, 6H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 203.3, 138.4, 133.8, 129.1, 127.7, 100.2, 96.3, 77.4, 77.1, 76.74, 64.7, 22.9, 15.3, 13.8, -2.8, -3.0. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.3. **HRMS** (ESI/TOF) *m/z*: [M + Na]$^+$ Calcd for $C_{15}H_{22}NaOSi$ 269.1332; Found 269.1334.

11-bromo-2-(2-(dimethyl(phenyl)silyl)-4-phenylbut-1-en-1-ylidene)undecan-1-ol (**2r**)



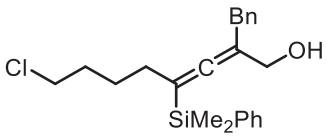
Following the General Procedure G. Colorless oil (88.1 mg, 86% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.58 – 7.52 (m, 2H), 7.42 – 7.36 (m, 3H), 7.30 – 7.24 (m, 2H), 7.22 – 7.16 (m, 1H), 7.15 – 7.10 (m, 2H), 3.97 – 3.78 (m, 2H), 3.42 (t, *J* = 6.9 Hz, 2H), 2.78 – 2.68 (m, 2H), 2.36 – 2.29 (m, 2H), 1.96 – 1.90 (m, 2H), 1.89 – 1.82 (m, 2H), 1.49 – 1.42 (m, 2H), 1.41 – 1.24 (m, 10H), 0.80 (s, 1H), 0.40 (s, 3H), 0.40 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 203.5, 142.0, 138.1, 133.9, 129.2, 128.4, 128.3, 127.8, 125.8, 101.5, 98.6, 63.8, 35.3, 34.0, 32.9, 31.0, 29.6, 29.5, 29.1, 28.8, 28.2, 28.1, -2.8, -2.9. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.2. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{29}H_{41}BrNaOSi$ 535.2002; Found 535.2006.

2-(4-chlorobutyl)-4-(dimethyl(phenyl)silyl)-6-phenylhexa-2,3-dien-1-ol (**2s**)



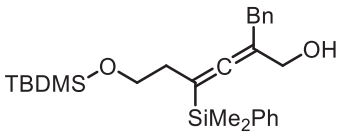
Following the General Procedure G. Colorless oil (62.1 mg, 78% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.61 – 7.49 (m, 2H), 7.43 – 7.35 (m, 3H), 7.31 – 7.24 (m, 2H), 7.23 – 7.17 (m, 1H), 7.16 – 7.09 (m, 2H), 3.96 – 3.79 (m, 2H), 3.52 (t, *J* = 6.7 Hz, 2H), 2.87 – 2.64 (m, 2H), 2.35 (t, *J* = 7.6 Hz, 2H), 2.01 – 1.88 (m, 2H), 1.84 – 1.73 (m, 2H), 1.56 – 1.40 (m, 2H), 0.77 (t, *J* = 6.1 Hz, 1H), 0.41 (s, 3H), 0.41 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 203.5, 141.9, 138.0, 133.9, 129.3, 128.4, 128.3, 127.9, 125.9, 100.7, 98.9, 63.9, 44.9, 35.2, 32.4, 30.8, 28.3, 25.3, -2.9, -3.0. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.0. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{24}H_{31}ClNaOSi$ 421.1725; Found 421.1732.

2-benzyl-8-chloro-4-(dimethyl(phenyl)silyl)octa-2,3-dien-1-ol (**2t**)



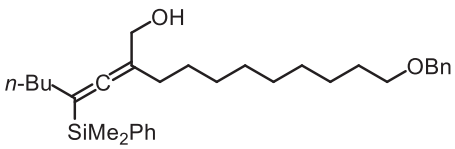
Following the General Procedure G. Colorless oil (63.0 mg, 82% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.46 – 7.33 (m, 5H), 7.32 – 7.26 (m, 2H), 7.25 – 7.15 (m, 3H), 4.07 – 3.96 (m, 2H), 3.45 (t, *J* = 6.6 Hz, 2H), 3.39 – 3.28 (m, 2H), 1.97 – 1.87 (m, 2H), 1.73 – 1.64 (m, 2H), 1.53 – 1.43 (m, 2H), 1.10 (s, 1H), 0.33 (s, 3H), 0.32 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 204.0, 139.5, 137.8, 133.8, 129.3, 129.2, 128.3, 127.8, 126.2, 101.1, 98.8, 77.4, 77.1, 76.8, 63.7, 45.0, 36.1, 32.0, 28.9, 26.3, -2.9, -2.9. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.1. **HRMS** (ESI/TOF) *m/z***:** $[M + Na]^+$ Calcd for $C_{23}H_{29}ClNaOSi$ 407.1568; Found 407.1564.

2-benzyl-6-((*tert*-butyldimethylsilyl)oxy)-4-(dimethyl(phenyl)silyl)hexa-2,3-dien-1-ol (**2u**)



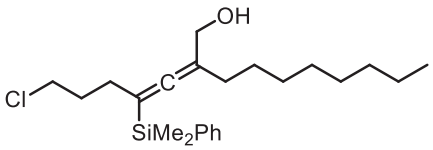
Following the General Procedure G. Colorless oil (68.7 mg, 76% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.47 – 7.40 (m, 2H), 7.39 – 7.31 (m, 3H), 7.30 – 7.25 (m, 2H), 7.24 – 7.20 (m, 1H), 7.18 – 7.14 (m, 2H), 3.99 (s, 2H), 3.69 – 3.59 (m, 1H), 3.58 – 3.48 (m, 1H), 3.38 – 3.24 (m, 2H), 2.10 (t, *J* = 6.9 Hz, 2H), 1.76 (s, 1H), 0.88 (s, 9H), 0.33 (s, 3H), 0.30 (s, 3H), 0.03 (s, 3H), 0.03 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 204.1, 139.5, 137.8, 133.9, 129.2, 129.1, 128.3, 127.8, 126.2, 101.2, 96.2, 63.0, 62.7, 36.0, 32.8, 26.0, 18.5, -3.0, -3.0, -5.2, -5.3. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ 20.4, -7.7. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{27}H_{40}NaO_2Si_2$ 475.2459; Found 475.2453.

11-(benzyloxy)-2-(2-(dimethyl(phenyl)silyl)hex-1-en-1-ylidene)undecan-1-ol (**2v**)



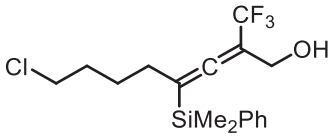
Following the General Procedure G. Colorless oil (89.6 mg, 91% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.58 – 7.51 (m, 2H), 7.42 – 7.33 (m, 7H), 7.32 – 7.26 (m, 1H), 4.53 (s, 2H), 4.04 – 3.92 (m, 2H), 3.49 (t, *J* = 6.6 Hz, 2H), 2.11 – 1.89 (m, 4H), 1.71 – 1.57 (m, 2H), 1.47 – 1.26 (m, 16H), 1.12 – 1.02 (m, 1H), 0.87 (t, *J* = 7.2 Hz, 3H), 0.40 (s, 3H), 0.39 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 203.2, 138.8, 138.4, 133.8, 129.1, 128.4, 127.8, 127.6, 127.5, 100.8, 99.4, 72.9, 70.6, 63.9, 31.5, 29.8, 29.6, 29.6, 29.6, 29.5, 29.2, 28.2, 26.2, 22.5, 14.0, -2.7, -2.8. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.2. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{32}H_{48}NaO_2Si$ 515.3316; Found 515.3312.

2-(5-chloro-2-(dimethyl(phenyl)silyl)pent-1-en-1-ylidene)decan-1-ol (**2w**)



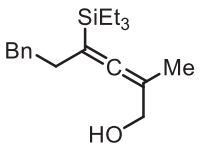
Following the General Procedure G. Colorless oil (73.0 mg, 93% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.46 – 7.40 (m, 2H), 7.31 – 7.24 (m, 3H), 3.93 – 3.82 (m, 2H), 3.41 (t, *J* = 6.6 Hz, 2H), 2.07 – 1.98 (m, 2H), 1.85 (td, *J* = 7.1, 4.0 Hz, 2H), 1.81 – 1.72 (m, 2H), 1.34 – 1.13 (m, 12H), 0.97 (s, 1H), 0.84 – 0.77 (m, 3H), 0.29 (s, 6H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 203.3, 137.9, 133.7, 129.3, 127.9, 101.7, 98.1, 77.4, 77.1, 76.7, 63.8, 44.5, 32.0, 31.9, 29.6, 29.5, 29.3, 29.1, 28.2, 26.9, 22.7, 14.1, -2.8, -3.0. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.0. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{23}H_{37}ClNaOSi$ 415.2194; Found 415.2185.

8-chloro-4-(dimethyl(phenyl)silyl)-2-(trifluoromethyl)octa-2,3-dien-1-ol (**2x**)



Following the General Procedure G. Colorless oil (66.6 mg, 92% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.56 – 7.48 (m, 2H), 7.44 – 7.36 (m, 3H), 4.17 (s, 2H), 3.46 (t, *J* = 6.5 Hz, 2H), 2.14 – 2.06 (m, 2H), 1.80 – 1.70 (m, 2H), 1.65 – 1.54 (m, 2H), 1.42 – 1.31 (m, 1H), 0.46 (s, 3H), 0.46 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 202.0, 202.0, 201.9, 201.9, 135.9, 133.8, 129.9, 128.7, 128.1, 126.0, 123.3, 120.6, 104.7, 95.6, 95.3, 95.0, 94.7, 59.4, 44.6, 31.7, 28.2, 28.1, 28.1, 28.1, 25.9, -3.4, -3.6. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -6.6. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{17}H_{22}ClF_3NaOSi$ 385.0973; Found 385.0970.

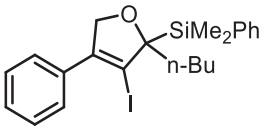
2-methyl-6-phenyl-4-(triethylsilyl)hexa-2,3-dien-1-ol (**3**)



Following the General Procedure I. Colorless oil (49.0 mg, 81% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.32 – 7.26 (m, 2H), 7.23 – 7.16 (m, 3H), 3.98 – 3.85 (m, 2H), 2.77 (t, *J* = 7.6 Hz, 2H), 2.35 – 2.24 (m, 2H), 1.66 (s, 3H), 1.04 (s, 1H), 0.95 (t, *J* = 7.9 Hz, 9H), 0.65 – 0.53 (m, 6H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 203.2, 142.2, 128.4, 128.3,

125.8, 95.6, 95.2, 64.8, 35.2, 30.9, 15.4, 7.3, 3.2. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ 2.5. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{19}H_{30}NaOSi$ 325.1958; Found 325.1962.

(2-butyl-3-iodo-4-phenyl-2,5-dihydrofuran-2-yl)dimethyl(phenyl)silane (**4**)

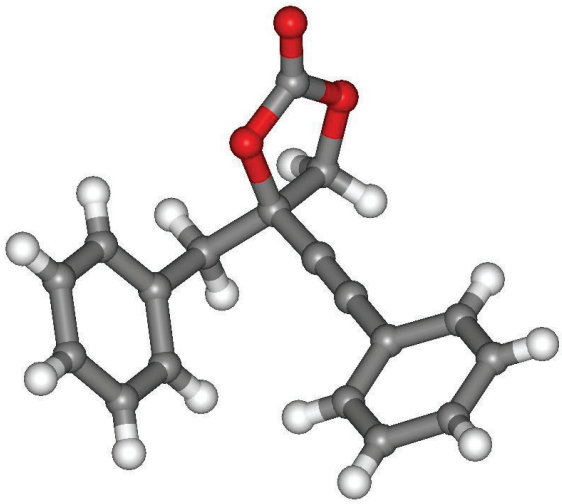


Following the General Procedure J. Pinkish oil (47.1 mg, 51% yield). Eluent 1% EtOAc/hexanes. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.71 – 7.66 (m, 2H), 7.41 – 7.29 (m, 6H), 7.26 – 7.22 (m, 2H), 4.87 (d, *J* = 11.5 Hz, 1H), 4.60 (d, *J* = 11.5 Hz, 1H), 2.06 (ddd, *J* = 14.3, 11.7, 4.5 Hz, 1H), 1.75 (ddd, *J* = 14.3, 11.6, 4.1 Hz, 1H), 1.51 – 1.23 (m, 4H), 0.93 (t, *J* = 7.2 Hz, 3H), 0.54 (s, 3H), 0.54 (s, 3H). **^{13}C NMR** (126 MHz, $CDCl_3$) δ 139.9, 136.9, 135.1, 134.4, 129.7, 128.7, 128.5, 127.9, 127.8, 94.4, 93.4, 79.3, 77.7, 77.4, 77.2, 34.5, 24.8, 23.3, 14.6, -3.0, -4.2. **^{29}Si NMR** (99 MHz, $CDCl_3$) δ -3.7. **HRMS** (ESI/TOF) *m/z*: $[M + Na]^+$ Calcd for $C_{25}H_{32}NaOSi$ 485.0768; Found 485.0771.

2.5.7 X-ray molecular structure for 1j

Procedure: single crystals of compound **1j** suitable for X-ray diffraction were obtained by slow evaporation from an ethyl acetate solution affording yellowish crystals. The measured crystal of **1j** were stable under atmospheric conditions; nevertheless, they were treated under inert conditions immersed in perfluoro-polyether as protecting oil for manipulation. Data Collection: measurements were made on a Bruker-Nonius diffractometer equipped with an APPEX II 4K CCD area detector, a FR591 rotating anode with MoKα radiation, Montel mirrors and a Kryoflex low temperature device (T = −173 °C). Full-sphere data collection was used with ω and ϕ scans. Programs used: Data collection Apex2 V2011.3 (Bruker-Nonius 2008), data reduction Saint+Version 7.60A (Bruker AXS 2008) and absorption correction SADABS V. 2008−1 (2008). Structure Solution: SHELXTL Version 6.10 (Sheldrick, 2000) was used.[21] Structure Refinement: SHELXTL-97-UNIX VERSION.

Crystallographic details for 1j: $C_{18}H_{14}O_3$, M_r = 278.29, monoclinic, $P2_1/c$, a = 16.1785(17) Å, b = 5.0735(5) Å, c = 17.4404(19) Å, α = 90°, β = 103.838(3)°, γ = 90°, V = 1390.5(3) Å^3, Z =4, ρ = 1.329 mg·M^{-3}, μ = 0.090 mm^{-1}, λ = 0.71073 Å, T = 100(2) K, F(000) = 584, crystal size = 0.30 × 0.10 × 0.05 mm^3, 2θ(min) = 2.592°, 2θ(max) = 67.53°, 21003 reflections collected, 5351 reflections unique (R_{int} = 0.0277), GoF = 1.064, R_1 = 0.0411 and wR_2 = 0.1106 [I>2σ(I)], R_1 = 0.0474 and wR_2 = 0.1149 (all indices), min/max residual density = −0.21/0.47 [e·Å^{-3}]. CCDC number 1994451.



X-ray molecular structure of **1j**.

2.6 References

1. (a) Ma, S. *Acc. Chem. Res*. **2009**, *42*, 1679. (b) Zimmer, R.; Dinesh, C. U.; Nandanan, E.; Khan, F. A. *Chem. Rev*. **2000**, *100*, 3067. (c) Muñoz, M. P. *Chem. Soc. Rev*. **2014**, *43*, 3164. (d) Chu, W.-D.; Zhang, Y.; Wang, J. *Catal. Sci. Technol.* **2017**, *7*, 4570. (e) Aubert, C.; Fensterbank, L.; Garcia, P.; Malacria, M.; Simonneau, A. *Chem. Rev.* **2011**, *111*, 1954. (f) Ye, J.; Ma, S. *Acc. Chem. Res*. **2014**, *47*, 989. (g) Rivera-Fuentes, P.; Diederich, F. *Angew. Chem. Int. Ed*. **2012**, *51*, 2818. (h) Lechel, T.; Pfrengle, F.; Reissig, H.-U.; Zimmer, R. *ChemCatChem* **2013**, *5*, 2100. (i) Lu, T.; Lu, Z.; Ma, Z.-X.; Zhang, Y.; Hsung, R. P. *Chem. Rev*. **2013**, *113*, 4862. (j) Soriano, E.; Fernández, I., *Chem. Soc. Rev.* **2014,** *43*, 3041. (k) Qiu, G.; Zhang, J.; Zhou, K.; Wu, J., *Tetrahedron* **2018,** *74*, 7290. (l) Yang, B.; Qiu, Y.; Bäckvall, J.-E., *Acc. Chem. Res.* **2018,** *51*, 1520.

2. For selected reviews and recent examples: (a) Yu, S.; Ma, S. *Angew. Chem. Int. Ed*. **2012**, *51*, 3074; (b) Hoffmann-Röder, A.; Krause, N. *Angew. Chem. Int. Ed*. **2004**, *43*, 1196. (c) Yu, S.; Ma, S. *Chem. Commun*. **2011**, *47*, 5384. (d) Pecchioli, T.; Cardona, F.; Reißig, H.-U.; Zimmer, R.; Goti, A. *J. Org. Chem.* **2017**, *82*, 5835. (e) Poulsen, P. H.; Li, Y.; Lauridsen, V. H.; Jørgensen, D. K. B.; Palazzo, T. A.; Meazza, M.; Jørgensen, K. A. *Angew. Chem. Int. Ed*. **2018**, *57*, 10661. (f) Li, G.; Huo, X.; Jiang, X.; Zhang, W. *Chem. Soc. Rev*. **2020**, *49*, 2060.

3. For selected examples of tri-substituted allenes: (a) Yu, S.; Sang, H. L.; Zhang, S.-Q.; Hong, X.; Ge, S. *Commun. Chem*. **2018**, *1*, 64. (b) Armstrong, R. J.; Nandakumar, M.; Dias, R. M. P.; Noble, A.; Myers, E. L.; Aggarwal, V. K. *Angew. Chem. Int. Ed.* **2018**, *57*, 8203. (c) Chu, W.-D.; Zhang, L.; Zhang, Z.; Zhou, Q.; Mo, F.; Zhang, Y.; Wang, J. *J. Am. Chem. Soc*. **2016**, *138*, 14558. (d) Trost B. M.; Zell, D.; Hohn, C.; Mata, G.; Maruniak, A. *Angew. Chem. Int. Ed*. **2018**, *57*, 12916. (e) Liao, Y.; Yin, X.; Wang, X.; Yu, W.; Fang, D.; Hu, L.; Wang, M.; Liao, J.

Angew. Chem. Int. Ed. **2020,** *59*, 1176. (f) Zhong, F.; Xue, Q.-Y.; Yin, L. *Angew. Chem. Int. Ed.* **2020,** *59*, 1562.

4. For a selection of tetra-substituted allenes: (a) Qian, D.; Wu, L.; Lin, Z.; Sun, J. *Nat. Commun*. **2017**, *8*, 567. (b) Scheipers, i.; Mück-Lichtenfeld, c.; Studer, A. *Angew. Chem. Int. Ed*. **2019**, *58*, 6545. (c) Yao, Y.; Zhu, G.; Chen, Q.; Qian, H.; Ma, S. *Org. Chem. Front*. **2019**, *6*, 304. (d) Hashimoto, T.; Sakata, K.; Tamakuni, F.; Dutton, M. J.; Maruoka, K. *Nat. Chem*. **2013**, *5*, 240. (e) Zheng, W.-F.; Zhang, W.; Huang, C.; Wu, P.; Qian, H.; Wang, L.; Guo, Y.-L.; Ma, S. *Nat. Catal.* **2019**, *2*, 997. (f) Bayeh-Romero, L.; Buchwald, S. L. *J. Am. Chem. Soc.* **2019**, *141*, 13788. (g) Tang, Y.; Xu, J.; Yang, J.; Lin, L.; Feng, X.; Liu, X. *Chem* **2018**, 4, 1658. (h) Cabrera-Lobera, N.; Velasco, N.; Sanz, R.; Fernández-Rodríguez, M. A. *Tetrahedron* **2019**, *75*, 4071. See also ref. 3b.

5. (a) Vyas, D. J.; Hazra, C. K.; Oestreich, M. *Org. Lett*. **2011**, *13*, 4462. (b) Hazra, C. K.; Oestreich, M. *Org. Lett*. **2012**, *14*, 4010. (c) Liu, Z.-L.; Yang, C.; Xue, Q.-Y.; Zhao, M.; Shan, C.-C.; Xu, Y.-H.; Loh, T.-P. *Angew. Chem. Int. Ed*. **2019**, *58*, 16538. (d) Ohmiya, H.; Ito, H.; Sawamura, M. *Org. Lett.* **2009**, *11*, 5. Also refer to: (e) Oestreich, M.; Hartmann, E.; Mewald, M. *Chem. Rev*. **2013**, *113*, 402. (f) Delvos, L. B.; Oestreich, M. in *Science of Synthesis Knowledge Update 2017/1*, Oestreich, M., Ed., Thieme, Stuttgart **2017**, p. 65–176.

6. Wang, M.; Liu, Z.-L.; Zhang, X.; Tian, P.-P.; Xua, Y.-H.; Loh, T.-P. *J. Am. Chem. Soc*. **2015**, *137*, 14830.

7. Yang, C.; Liu, Z.-L.; Dai, D.-T.; Li, Q.; Ma, W.-W.; Zhao, M.; Xu, Y.-H. *Org. Lett*. **2020**, *22*, 1360.

8. (a) Kessler, S. N.; Hundemer, F.; Bäckvall, J.-E. *ACS Catal*. **2016**, *6*, 7448. (b) Ye, J.; Fan, W.; Ma, S. *Chem. Eur. J*. **2013**, *19*, 716. (c) Mundal, D. A.; Lutz, K. E.; Thomson, R. J. *J. Am. Chem. Soc.* **2012**, *134*, 5782. (d) Jiang, Y.; Diagne, A. B.; Thomson, R. J.; Schaus, S. E. *J. Am. Chem. Soc*. **2017**, *139*, 1998.

9. (a) Colvin, E. W.; König, W. A.; Loreto, M. A.; Rowden, J. Y.; Tommasini, I. *Bioorg. Med. Chem. Lett.* **1993**, *3*, 2405. (b) Lempke, L.; Sak, H.; Kubicki, M.; Krause, N. *Org. Chem. Front*. **2016**, *3*, 1514. (c) Sun, T.; Deutsch, C.; Krause, N. *Org. Biomol. Chem*. **2012**, *10*, 5965, (d) Semple, J. E.; Wang, P. C.; Lysenko, Z.; Joullie, M. M. *J. Am. Chem. Soc.* **1980**, *102*, 7505. (e) Deska, J.; Bäckvall, J.-E., *Org. Biomol. Chem.* **2009,** *7*, 3379. (f) Grandclaudon, C.; Michelet, V.; Toullec, P. Y. *Org. Lett.* **2016,** *18*, 676.

10. (a) Shen, R.-W.; Yang, J.-L.; Zhao, H.-P.; Feng, Y.; Zhang, L.-X.; Han, L.-B. *Chem. Commun*. **2016**, *52*, 11959. (b) Miura, T.; Shimada, M.; Mendoza, P. D.; Deutsch, C.; Krause, N.; Murakami, M. *J. Org. Chem*. **2009**, *74*, 6050. (c) Chang, X.-H.; Liu, Z.-L.; Luo, Y.-C.; Yang, C.; Liu, X,-W.; Da, B.-C.; Li, J.-J.; Ahmad, T.; Loh, T.-P.; Xu, Y.-H. *Chem. Commun.* **2017**, *53*, 9344. (d) Asikainen, M.; Krause, N. *Adv. Synth. Catal*. **2009**, *351*, 2305. (e) Fürstner, A.; M. Méndez, M. *Angew. Chem. Int. Ed*. **2003**, *42*, 5355. (f) Darcel, C.; Bruneau, C.; Dixneuf, P. H. *J. Chem. Soc*., *Chem. Commun*. **1994**, 1845.

11. See for instance: (a) Martín, C.; Fiorani, G.; Kleij, A. W. *ACS Catal*. **2015**, *5*, 1353. (b) Rajjak Shaikh, R.; Pornpraprom, S.; D'Elia, V. *ACS Catal*. **2018**, *8*, 419.

12. For a few reviews/examples: (a) Guo, W.; Gómez, J. E.; Cristòfol, À.; Xie, J.; Kleij, A. W. *Angew. Chem. Int. Ed.* **2018**, *57*, 13735. (b) Cai, A.; Guo, W.; Martínez-Rodríguez, L.; Kleij, A. W. *J. Am. Chem. Soc*. **2016**, *138*, 14194. (c) Guo, W.; Kuniyil, R.; Gómez, J. E.; Maseras, F.; Kleij, A. W. *J. Am. Chem. Soc.* **2018**, *140*, 3981.

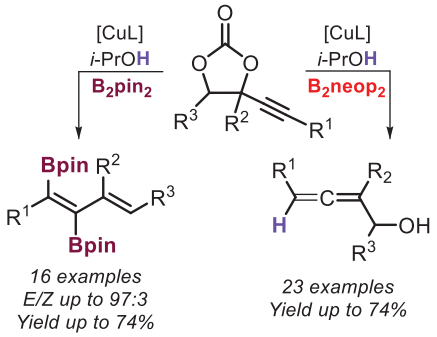
13. (a) Gómez, J. E.; Cristofol, A.; Kleij, A. W. *Angew. Chem. Int. Ed*. **2019**, *58*, 3903. (b) Tian, L.; Gong, L.; Zhang, X. *Adv. Synth. Catal.* **2018**, *360*, 2055. (c) Zhang, Y.-C.; Zhang, B.-W.; Geng, R.-L.; Song, J. *Org. Lett.* **2018**, *20*, 7907. (d) Zhang, Z.-J.; Zhang, L.; Geng, R.-L.; Song, J.; Chen, X.-H.; Gong, L.-Z. *Angew. Chem.*

Int. Ed. **2018**, *58*, 12190. For related work: (e) Gómez, J. E.; Guo, W.; Gaspa, S.; Kleij, A. W. *Angew. Chem. Int. Ed*. **2017**, *56*, 15035.

14. Tang, X.; Woodward, S.; Krause, N. *Eur. J. Org. Chem*. **2009**, 2836. See also ref. 7.
15. For more details, see CCDC-1994451 and the Experimental Section.
16. Note that the choice for CuCN as precursor and $PhMe_2SiBPin$ as silyl reagent was based on previous success in related silylation reactions, see for instance refs. 5a-b and 10c. The choice for the ICy carbene ligand was inspired by the work from Hoveyda in the protosilylation of terminal alkynes, see: Meng, F.; Jang, H.; Hoveyda, A. H. *Chem. Eur. J*. **2013**, *19*, 3204.
17. Under similar conditions, conversion of **1o** afforded its Et_3Si-substituted 2,3-allenol product in 73% NMR yield.
18. Cristòfol, À.; Böhmer, C.; Kleij, A. W. *Chem. Eur. J* **2019**, *25*, 15055.
19. Li, W.; Wollenburg, M.; Glorius, F. *Chem. Sci.* **2018**, *9*, 6260.
20. Triantafyllakis, M.; Sfakianaki, K.; Kalaitzakis, D.; Vassilikogiannakis, G. *Org. Lett.* **2018**, *20*, 3631.
21. Sheldrick, G. M. SHELXTL Crystallographic System, version 6.10; Bruker AXS, Inc.: Madison, WI, **2000**.

Chapter 3

Cu-mediated Dichotomic Borylation of Alkyne Carbonates: Stereoselective Access to (*E*)-1,2-Diborylated 1,3-Dienes versus Traceless Monoborylation affording *α*-Hydroxyallenes



This chapter has been published in:

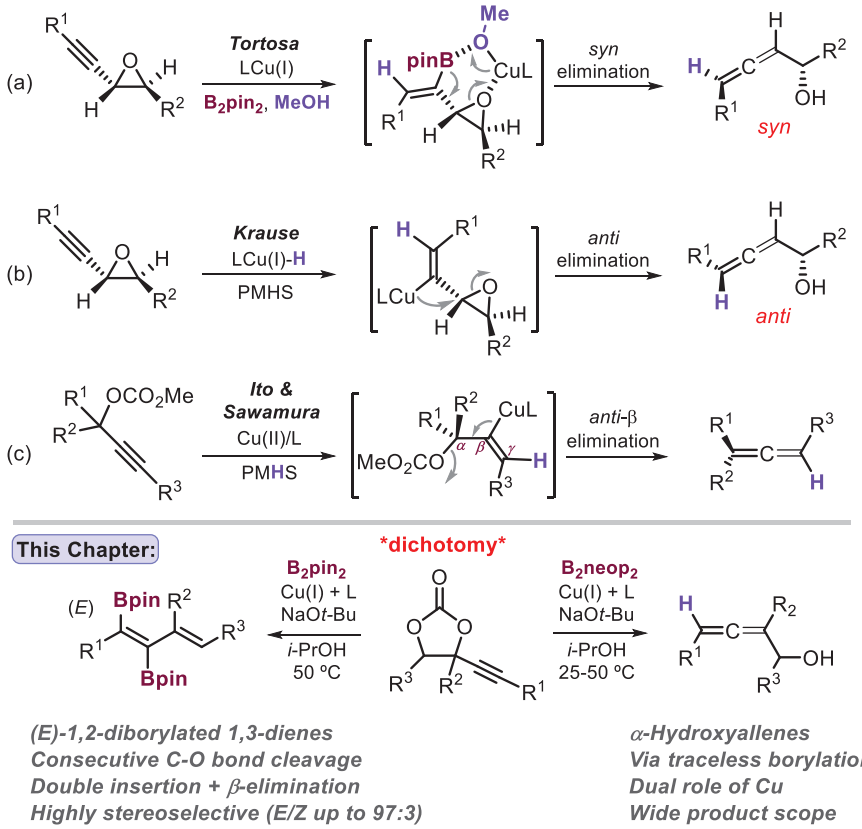
Guo, K.; Kleij, A. W. *Angew. Chem. Int. Ed.* **2021**, *60*, 4901-4906.

3.1 Introduction

Organoboronate compounds play a privileged role in organic synthesis representing benchmark-stable synthons featuring C–B bonds that can be utilized to create a wide range of complex molecules.[1] In particular, bis(pinacolato)diboron (B_2pin_2) and its congeners are versatile borylating agents which have enabled the preparation of a great diversity of (un)saturated boron derivatives including allyl, allenyl, propargyl, vinyl and alkyl/aryl boronates through well-established catalytic carbon-boron bond formation processes.[2] Many elegant strategies have been developed over the years, and in this context the borylation of propargyl substrates displays a particular diversity of reactivity patterns that can be controlled by an appropriate transition metal catalyst.

Pioneering work reported by Ito and Sawamura in 2008 illustrated the regio- and stereoselective borylation of linear propargyl carbonates under Cu catalysis affording a variety of mono-borylated, tri- and tetrasubstituted allenes.[3] In 2017, Tortosa *et al.* demonstrated that propargylic epoxides can be conveniently transformed into their formally reduced *α*-hydroxyallenes by Cu-catalysis in the presence of B_2pin_2 and methanol (Scheme 1a),[4a] with a *syn*-elimination of the Bpin group playing a pivotal role in this process. The combination of B_2pin_2 and an alcohol as a reducing medium mimics the utilization of copper hydride chemistry reported independently by Krause (Scheme 1b)[5] and Ito/Sawamura (Scheme 1c).[6] These authors demonstrated that Cu-mediated formal reduction of propargylic epoxides and propargylic linear carbonates could be accomplished, respectively, by PMHS (polymethylhydrido-siloxane) as the stoichiometric hydride source offering a straightforward synthetic route towards allenes.

The exploration of the reactivity of both allylic[7] and alkynyl cyclic carbonates and similar heterocycles[8] as modular substrates in transition metal catalyzed stereoselective transformations has significantly expanded over the last five years. In particular, we found that Cu-catalyzed decarboxylative silylation of cyclic carbonates functionalized with alkyne groups is feasible affording a library of tetrasubstituted 2,3-allenols.[9]



Scheme 1. Formal reduction of propargylic substrates (a-c) and dichotomic reactivity observed in the Cu-mediated conversion of alkynyl cyclic carbonates in the presence of borylating reagents (**This Chapter**).

3.2 Project Aims and Strategy

Inspired by the pioneering work described in Scheme 1[4a,5-6] and the structural versatility of alkynyl cyclic carbonates,[8a-e,9] we envisioned that borylation of a new type of propargylic surrogate could significantly expand the diversity of functional and highly substituted α-hydroxyallene scaffolds, which are useful building blocks for heterocyclic chemistry and natural product synthesis.[10] In the course of these studies, we discovered an unexpected though unique dichotomic behavior of the borylating agent providing selective pathways

leading either to an (*E*)-diborylated 1,3-diene or α-hydroxyallene product using the same catalytic system. Apart from the synthetic utility of the modular alkynyl cyclic carbonates serving as common substrates for product diversion, the reasons for this remarkable dichotomic reactivity have also been studied through a series of mechanistic control reactions.

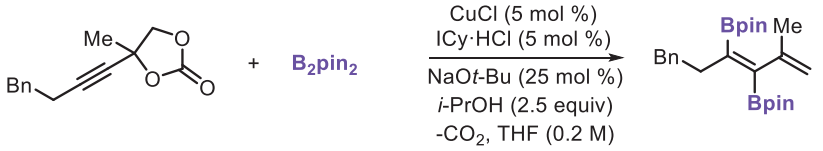
3.3 Results and discussion

First, cyclic carbonate **S1** and B_2pin_2 were combined to examine the influence of various reaction parameters on the selectivity of the borylation process (Table 1). We initially pre-screened a wide series of ligands, bases and solvents using a high-throughput experimentation approach (see the Experimental Section). From this first screening phase, we selected the carbene precursor ICy·HCl (1,3-dicyclohexylimidazolium hydrochloride), NaO*t*-Bu as base and THF/*i*-PrOH as medium on the basis of the selectivity and yield (66%) for 1,2-diborylated 1,3-diene product **1** and the overall stereoinduction (*E/Z* = 33:1). [11]

Hereafter we set out to screen the influence of the amount of B_2pin_2, base additive, solvent and reaction temperature. As can be judged from Table 1, the reaction proved to be inadequate in the absence of either the Cu precursor, base additive or the carbene ligand (entries 1-3). The protic additive (*i*-PrOH) also plays an important role as its presence significantly improves the yield of **1** and the stereoinduction (entry 4). Lowering or increasing the amount of CuCl, concentration, the amount of B_2pin_2 or the reaction temperature did not positively affect the reaction efficiency (entries 5-11). Replacing the protic additive by HFIP (hexafluoroisopropanol, entry 12) gave an intractable reaction mixture whereas the use of *t*-amyl-alcohol (entry 13) demonstrated somewhat lower catalytic potential in terms of yield of **1** and its *E/Z* ratio. Further changes in solvent and base (entries 14-18) did also not improve the outcome of this conversion. Finally, several Cu(I) and Cu(II) precursors were scrutinized (entries 19-22) showing that both types of precursors allow for effective catalysis. Compared to CuCl, the utilization of CuCN at room temperature produced a slightly lower yield of **1** (entry 21), though at 50 ºC the presence

of this precursor led to the best catalytic performance furnishing the diborylated product in 73% isolated yield and maintaining high stereocontrol (entry 22 versus entry 11). The identity of the main stereoisomer (*E*) was confirmed by X-ray analysis (see the inset in Table 1, details in the Experimental Section).[12]

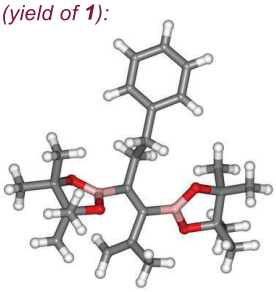
Table 1. Cu-mediated transformation of alkynyl cyclic carbonate **S1** and B_2pin_2 under various reaction conditions leading to diborylated product **1**.[a]



S1, 0.20 mmol | 0.50 mmol | **1**, 66%, *E/Z* = 97:3

*variations from the reaction conditions (yield of **1**):*

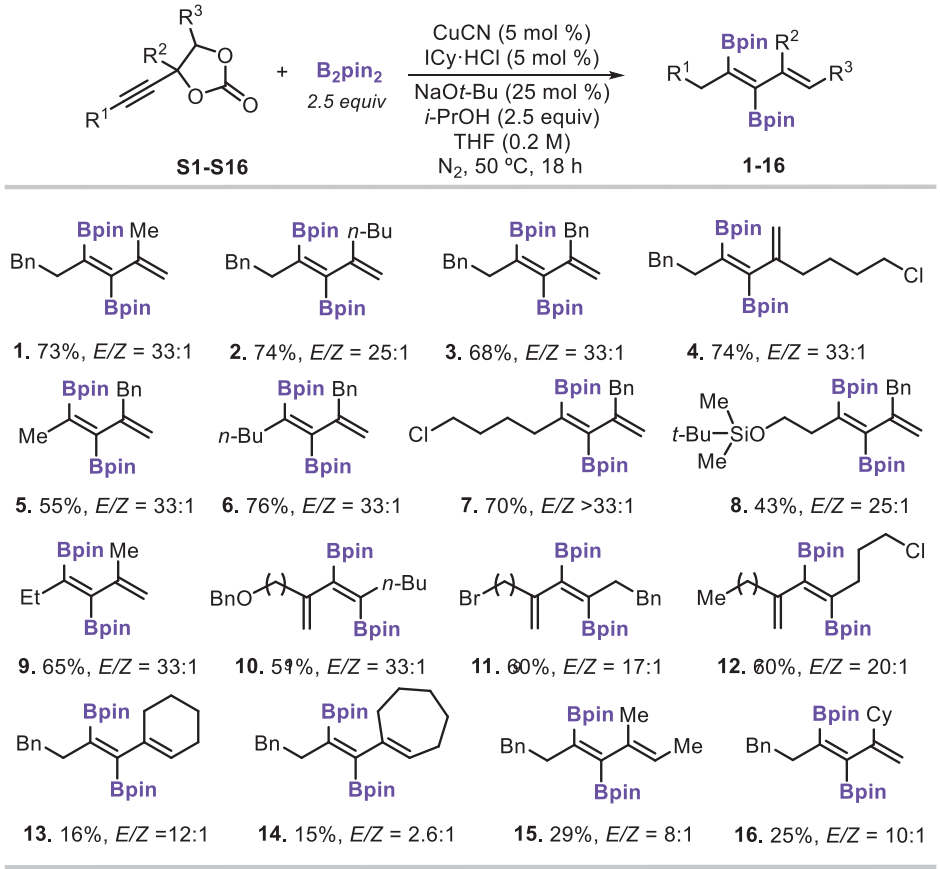
1. No Cu (0%)
2. No base (0%)
3. No ligand (0%)
4. No *i*-PrOH (32%, *E/Z* = 1.6:1)
5. 10 mol% Cu (50%)
6. Concentration 0.4 M (46%)
7. Concentration 0.1 M (54%)
8. 1.8 equiv B_2pin_2 (57%)
9. 3 equiv B_2pin_2 (59%)
10. reaction at 0 °C (60%)
11. reaction at 50 °C (62%)
12. No *i*-PrOH but HFIP (0%)[b]
13. No *i*-PrOH but *t*-amyl-OH (54, *E/Z* = 5:1)
14. DCM as solvent (0%)
15. ACN as solvent (0%)
16. Et_2O as solvent (44%)



17. Cs_2CO_3 as base (51%)
18. NaOMe as base (20%)
19. CuBr/CuOAc (50/4%)
20. $CuCl_2$/$CuOTf_2$/$CuOAc_2$ (48/15/36%)
21. CuCN (60%), CuCl (66%)
22. 50 °C: CuCN (73%)
23. Mes-Cu: 47% (25 °C), 62% (50 °C)

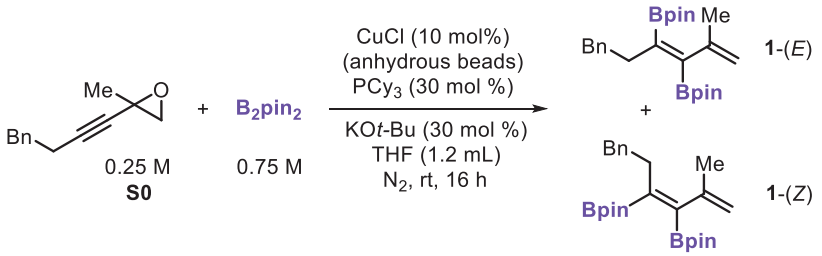
[a] The comparative reaction conditions are shown in the scheme. If not stated otherwise, the *E/Z* ratio of **1** is similar to the one observed using CuCl/ ICy·HCl as catalyst, NaO*t*-Bu as base, and *i*-PrOH/THF as medium. [b] A complex product mixture was obtained.

The scope of this stereoselective diborylation process (Scheme 2) was further investigated using a more ample set of alkynyl cyclic carbonate precursors (**S1-S16**: for their synthesis, see the Experimental Section).[9] Diborylated compounds **1–12** were produced with a high degree of stereocontrol, appreciable yields and reasonable skeletal variation useful in post-synthetic operations.[11b]



Scheme 2. Scope of 1,2-diborylated 1,3-dienes (**1-16**) using various alkynyl cyclic carbonates **S1-S16** and B_2pin_2 as reagents under the optimized catalytic conditions (Table 1, entry 22). All yields are of the isolated product, *E/Z* ratios were determined by ^{1}H NMR $CDCl_3$).

Products **13**–**16**, however, were isolated in low yields and with substantially lower levels of stereoinduction which is ascribed to the increasing steric impediment exerted by the R^2 and R^3 substituents of the cyclic carbonate precursor. These combined results (Schemes 2 and 3) clearly show that rather different reactivity and chemoselectivity is observed in the conversion of the alkynyl-substituted cyclic carbonates versus epoxides in the presence of B_2pin_2 and a protic additive (cf., Scheme 1a).



1. No change: **1**, 80%, *E/Z* = 3.7:1
2. With 50 mol% of Cu: **1**, 75%, *E/Z* = 4.4:1
3. CuCl (powder): **1**, 29%, *E/Z* = 3.8:1
4. As for 3, *i*-PrOH: **1**, 20%, *E/Z*>20:1
5. Using conditions from entry 22, Table 1: **1**, 50%, *E/Z*>20:1

*Isolated yields of **1***
E/Z ratios determined by ^1H NMR

Scheme 3. Influence of propargylic epoxide **S0** and supporting ligand in the Cu-catalyzed diborylation process leading to **1**.

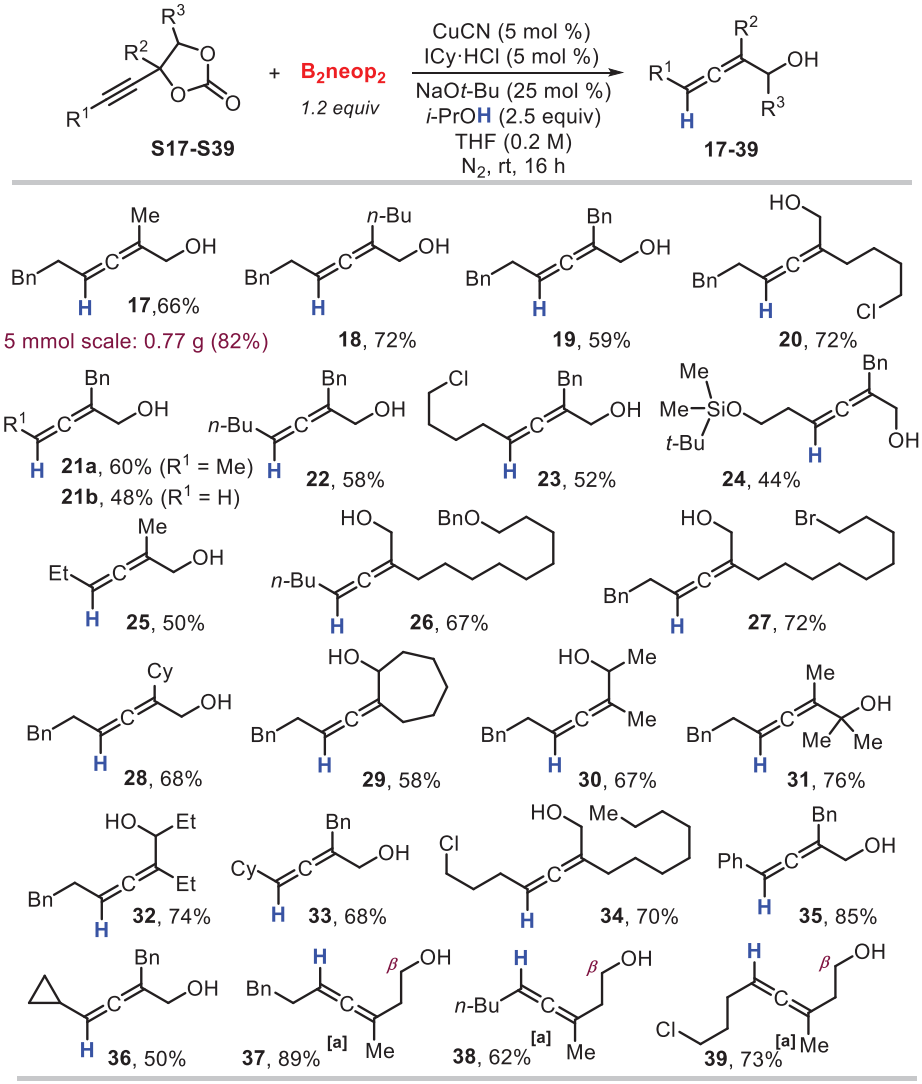
The nature and influence of the propargylic precursor and the supporting ligand was further examined (Scheme 3, entry 1). We were able to reproduce the outcome of the diborylation procedure reported by Szabó et al.[11a] using a propargylic epoxide (**S0**) providing a rather similar yield of **1** (80%) and *E/Z* ratio for the isolated product (4:1). The nature of the Cu precursor (entries 3 and 4) had a significant impact on the yield of **1**, whereas the presence of *i*-PrOH gave **1** in low yield though with high stereofidelity (entry 4, *E/Z*>20:1). By applying the optimized conditions from Table 1 (entry 22: CuCN/ICy·HCl), propargylic epoxide **S0** was converted into diborylated product **1** (50%) with an *E/Z* ratio of >20:1 (entry 5). These control experiments demonstrate that a Cu-

carbene catalyst with a protic additive is able to produce 1,2-diborylated 1,3-dienes with significantly higher levels of stereoinduction.

We next wondered whether the scope of 1,2-diborylated 1,4-dienes could be further amplified by variation of the diboron(4) compounds. We considered the use of B_2neop_2 [bis(neopentyl glycolato)diboron], as this reagent is commercially available and has frequently been used in other types of organic transformations.[2i,13] By applying the same catalyst and reaction conditions reported for the synthesis of diborylated compounds **1-16** (Scheme 2), we observed the primary formation of a different product from alkynyl cyclic carbonate **S1**, which was identified as the formally reduced α-hydroxyallene **17** (67%, Scheme 4). The yield of **17** did not change (66%) when lowering the reaction temperature from 50 to 25 ºC, and furthermore only a slight excess (1.2 equiv) of B_2neop_2 was required. The reaction could be easily scaled up (*i.e.*, using 5 mmol of starting carbonate) delivering **17** in 82% yield (0.77 g).

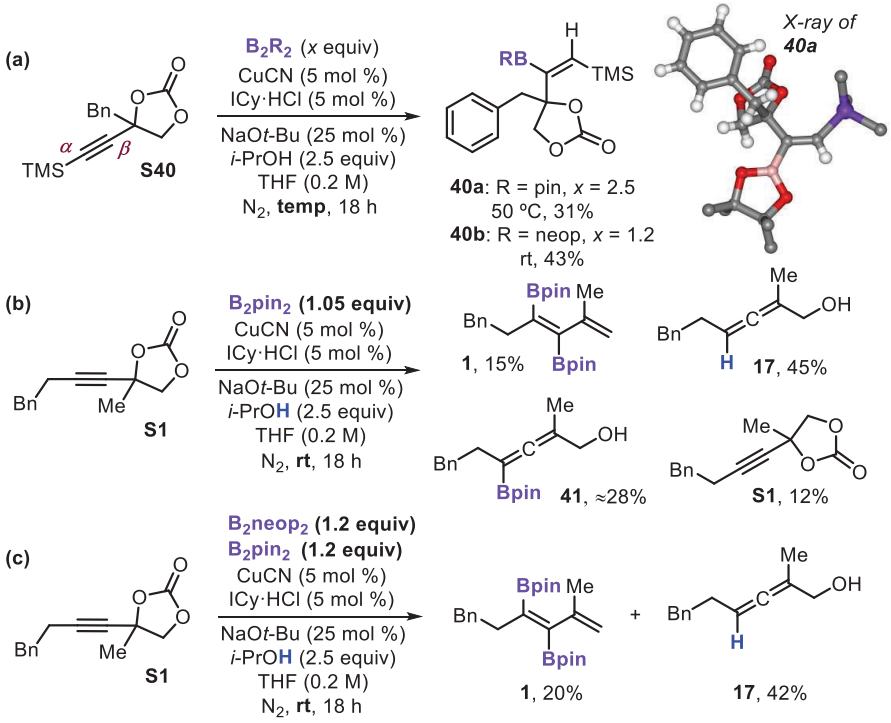
With these conditions in hand, we explored the scope of this unusual borylation driven dichotomy.[14] Various alkynyl cyclic carbonates (**S17**-**S39**) could be conveniently converted into their (reduced) α-hydroxyallenes (Scheme 4, **18**–**36**) with ample diversity in the substitution and functional groups in the presence of B_2neop_2 and the same catalyst employed to access the diborylated 1,3-dienes (Scheme 2, **1–16**). Most of the allene products were isolated in appreciable yields. Unlike in the case of diborylation, the presence of more rigid or more sterically demanding substituents in the carbonate substrate did not pose a restriction to the formation of the α-hydroxyallenes (cf., **28**–**32**) and the developed protocol allows for the presence of various fragments in the final product including alkyl halides (**20**, **23**, **27** and **34**), protected alcohols (cf., **24** and **26**) and cycloalkane rings (**29** and **36**). Gratifyingly, six-membered alkynyl cyclic carbonate precursors (see the Experimental Section for more details) were also productive substrates in this catalytic methodology giving straightforward access to α-hydroxyallenes **37–39** in good yields. The use of six-membered alkynyl carbonates further expands the repertoire of hydroxyallene scaffolds and validates the great versatility and synthetic potential of these

functionalized cyclic carbonates compared to the significantly less modular propargylic epoxides.



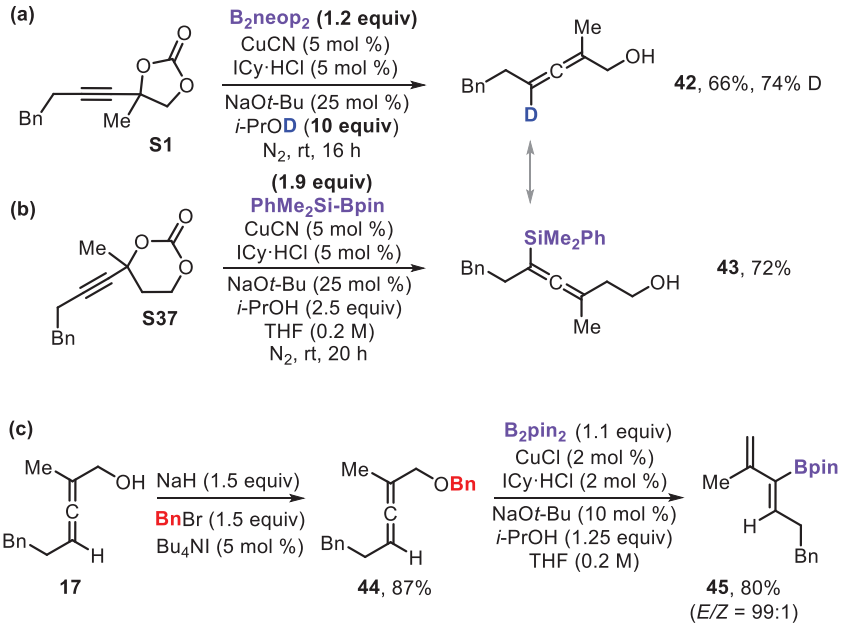
Scheme 4. Formal reduction of alkynyl cyclic carbonates **S17-S39** in the presence of B_2neop_2 under similar reaction conditions used in Table 1, entry 22. All yields are of the isolated product. [a] The reaction time was 20 h.

The remarkable difference in chemoselectivity between the catalytic experiments performed in the presence of B_2pin_2 or B_2neop_2, despite of their structural similarity, was then scrutinized in detail through several control experiments and synthetic extensions (Scheme 5). First, the diborylation of the TMS-protected alkynyl cyclic carbonate **S40** (Scheme 5a) was attempted. However, the major constituent of the product mixture turned out to be a mono-β-borylated cyclic carbonate product using either B_2pin_2 or B_2neop_2. The identity and atom connectivity of **40a** was unambiguously established by X-ray crystallography.[12]



Scheme 5. Mechanistic control experiments.

This β-regioselectivity is believed to be driven by electronic control, as previously Sun and coworkers described that silyl substituents act as strong β-regio-controlling substituents in propargylic borylations.[15] This precedent not only allows to rationalize the β-borylation of **S40**, but also points at the α-borylation being the productive pathway towards 1,3-diborylation.



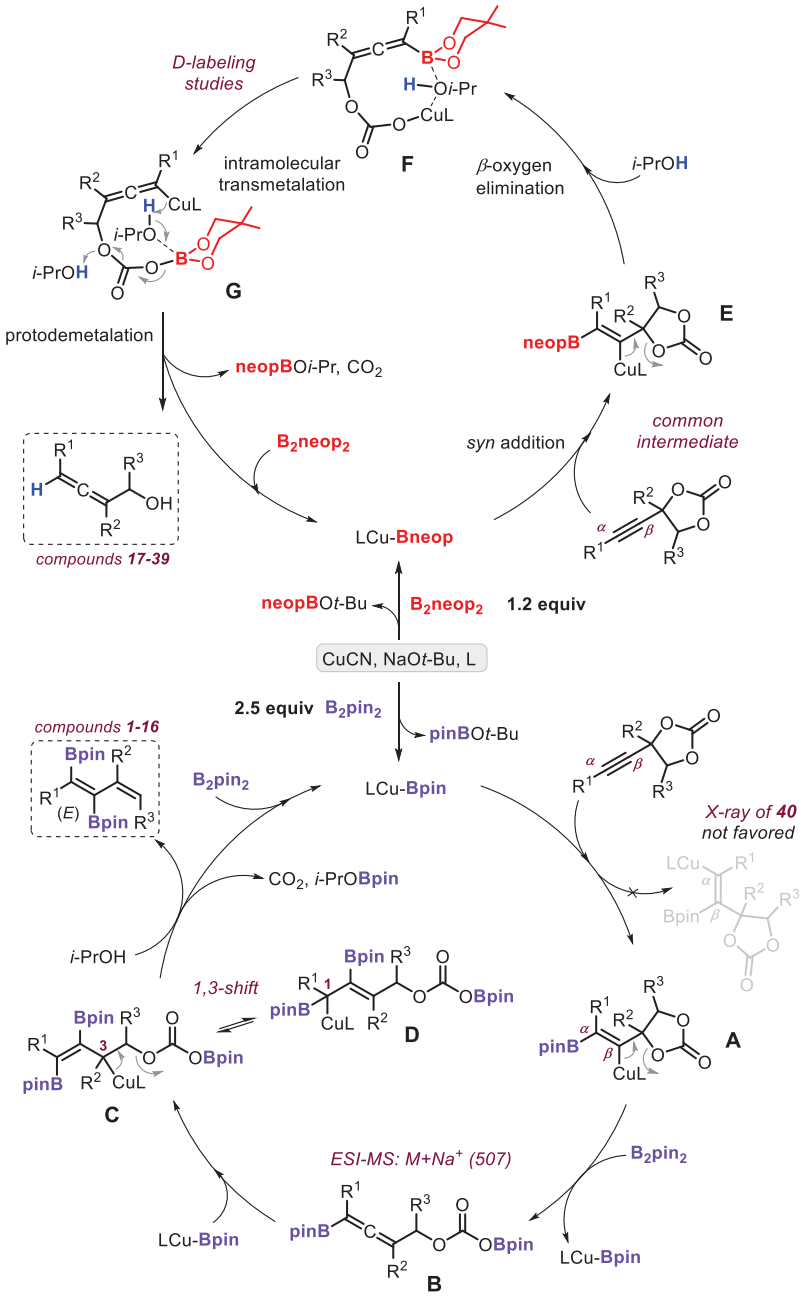
Scheme 6. Additional mechanistic control experiments.

Intrigued by this observation, we then performed the borylation of substrate **S1** under the optimized reaction conditions using a slight excess (1.05 equiv) of B_2pin_2 (Scheme 5b). Four major components were identified by ^1H NMR spectroscopy in the reaction mixture being unreacted starting material **S1** (12%), diborylated 1,4-diene **1** (15%), α-hydroxyallene **17** (45%) and the mono-borylated allene **41** (~28%, cf. α-borylation of the alkyne unit; see the Experimental Section for details).[16] These data illustrate that an excess of B_2pin_2 is required to favor the formation of the diborylated diene, and that the mono-borylated allene **41** is a likely precursor to **1**. In the absence of a sufficiently large excess

of B_2pin_2 alternative parasitic pathways may be favored. The formation of *α*-hydroxyallene **17** as the major compound under these reaction conditions suggest that alcohol-promoted proto-deborylation of **41** is competitive.

Next a competition experiment was carried out adding both B_2pin_2 and B_2neop_2 to a mixture of **S1** and the Cu-carbene catalyst (Scheme 5c). No scrambling of boronate groups was observed for **1**, and both **1** (20%) and **17** (45%) could be isolated pointing to similar order of magnitude kinetics of the first borylation step in both manifolds. This suggests that the origin of the observed dichotomy in the process is related to the relative kinetics of the second borylation step versus proto-deborylation. Since the B–C bond in the Bneop functionalized allene intermediate reminiscent to **41** is sterically more susceptible for transmetalation followed by protonation, the preferred formation of the formally reduced *α*-hydroxyallenes (Scheme 4) in the presence of B_2neop_2 and the Cu-carbene complex can be rationalized.

The proposed proto-demetalation step induced by the alcohol additive was examined converting substrate **S1** into *α*-hydroxyallene **42** (Scheme 6a) in the presence of *i*-PrOD providing the product with 74% deuterium incorporation being in line with our mechanistic hypothesis. Finally, the six-membered alkynyl cyclic carbonate **S37** was converted into the silylated *β*-hydroxyallene **43** in 72% yield demonstrating a useful amplification of this type of building block,[9] and *α*-hydroxyallene **17** was transformed via a two-step process into the mono-2-borylated 1,3-diene **45** in good yield and with high stereoselectivity (Scheme 6b+c).[17] Interestingly, for these latter conversions virtually the same catalytic process was effective as the one leading to the diborylated synthons (see Scheme 2) and *α*-hydroxyallenes (see Scheme 4).



Scheme 7. The proposed manifolds for 1,2-diborylated 1,3-diene (bottom half) and α-hydroxyallene formation (upper part). L stands for the carbene ligand ICy.

Based on our observations and control experiments, a mechanistic description of the borylation process is presented in Scheme 7. After initial formation of a Cu(I)-boryl species (lower part), the reaction advances with an addition-elimination sequence that involves the first borylation step (**A**), carbonate ring-opening and elimination of the Cu complex providing a borylated allene with a pendent –OCO_2Bpin leaving group (**B**). Evidence for the intermediacy of **B** was found by ESI(+)-MS (see the SI), and its structure resembles generically the one proposed by Szabó et al.[11a] Subsequently, the allyl-OCO_2Bpin species **B** will then undergo a second Cu-catalyzed borylation via a S_N2'-type mechanism, after which the Cu-catalyst is regenerated via protodemetalation. A 1,3-sigmatropic rearrangement involving the [CuL] complex **D** allows to explain 1,2-diborylated 1,3-diene formation from the envisioned productive 3-metaled isomer **C**. The requisite for having first a borylation on the *α*-carbon of the alkyne is supported by the isolation of compounds **40a** and **40b** (Scheme 5a), as *β*-borylation would not allow for these envisioned consecutive steps to take place. An excess (2.5 equiv) of B_2pin_2 in the proposed manifold agrees well with the experimental observation of a mixture of compounds when a virtually stoichiometric amount was present (Scheme 5b). Under these conditions, the concomitant formation of mono-borylated allenol **41** is noted being a likely precursor to the 1,2-diborylated 1,3-diene product. The whole process involves two C–O bond scission steps, with the second one leading to an (*E*)-configured diborylated alkene under steric control.

In the case of B_2neop_2 (upper part of Scheme 7), the reaction takes a different course though the first addition step (**E**) is reminiscent to the one (**A**) based on B_2pin_2. Upon *β*-oxygen elimination, a borylated allene carbonate copper species **F** is formed that, with the assistance of *i*-PrOH,[4,18] can undergo a directing group controlled intramolecular transmetalation (**G**).[19] The so-formed copper allene borocarbonate intermediate **G** would produce the final *α*-hydroxy allene via a protonation process while releasing CO_2 and neopBO*i*-Pr, and regenerating LCu(O*i*-Pr) for subsequent turnover. The competition experiment using a 1:1 molar ratio of both B_2pin_2 and B_2neop_2 (Scheme 5c) and the deuterium labeling experiment (Scheme 6a) are in line with this scenario, and the apparent

easier activation of the C–Bneop bond by the Cu complex will lead preferentially to the *α*-hydroxyallene product.

3.4 Conclusion

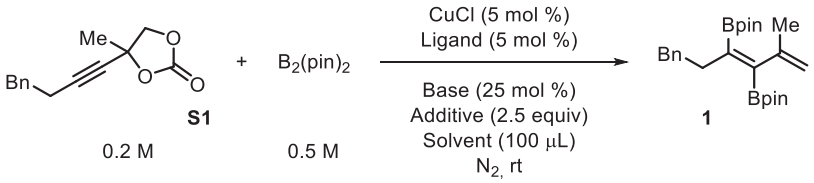
In summary, we have discovered a new dichotomic behavior of diboron(4) reagents in the Cu-mediated catalytic conversion of alkynyl cyclic carbonates. This new process significantly expedites the synthesis of useful 1,2-diborylated 1,3-dienes, and *α*- and *β*-hydroxy allenes using a mild and simple catalytic approach. Virtually the same catalytic protocol allows for the stereoselective conversion of *α*-hydroxyallenes into 2-borylated 1,3-dienes, making the developed catalyst thus a privileged system for the preparation of wide range of synthetically valuable synthons.

3.5 Experimental Section

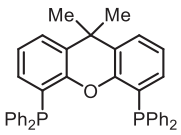
3.5.1 General information

Please refer to section **2.5.1.**

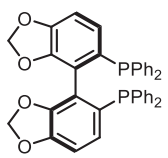
3.5.2 High throughput experimentation (HTE) studies



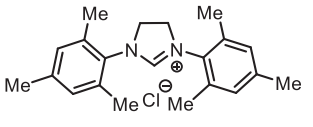
General procedure: In an N_2-filled glovebox, all the ligands were pre-dosed in 1 mL vials and placed in a pre-selected position on a multi-well plate. CuCl, bases, additives, the cyclic carbonate **S1** and $B_2(pin)_2$ were prepared in stock solutions in appropriate solvents. Proper amounts of CuCl, bases and additives were added into the vials with pro-dosed ligands. After stirring for 5 min at room temperature (r.t.), the vials were charged with proper amounts of cyclic carbonate **S1** and $B_2(pin)_2$. The vials were sealed and moved out of the glovebox. The reactions were allowed to stir at r.t. for 18 h. After the reactions were terminated, the reaction mixtures were charged with a proper amount of biphenyl (in 0.5 mL of acetonitrile) as internal standard. After thorough mixing, centrifugal separation, the solution phase of the mixtures was analyzed by UPLC-MS and GC-MS.



Xantphos



(*R*)-Segphos



1,3-dimesitylimidazolidinium chloride

<u>Parameters</u> used: **Ligands**: Xantphos, (*R*)-Segphos, PCy_3 and 1,3-dimesitylimidazolidinium chloride; **Bases**: LiO*t*-Bu, NaO*t*-Bu and KO*t*-Bu; **Additives**: MeOH, *t*-BuOH and *i*-PrOH; **Solvents**: THF and toluene.

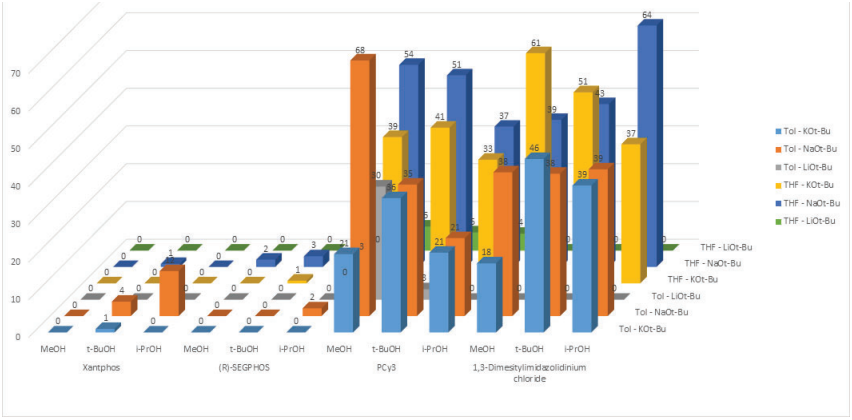
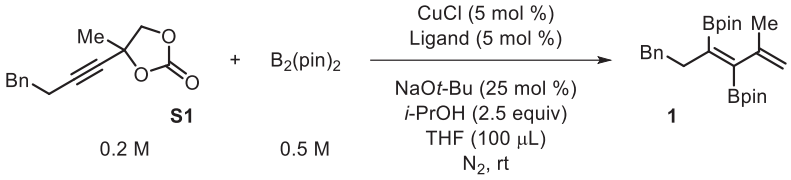


Figure S1. Graphical representation of the yield of 1,2-diborylated 1,3-diene **1** under different reaction conditions.



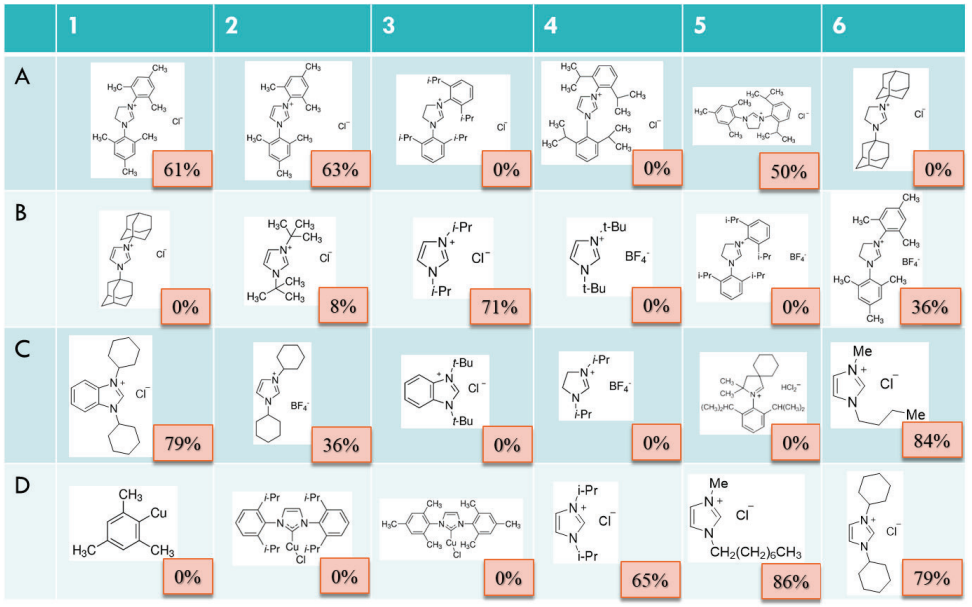


Figure S2. Yield of **1** using various NHC ligands.

Even though the use of PCy_3, NaO*t*-Bu and MeOH in toluene give comparable yields as the one obtained with 1,3-dimesitylimidazolidinium chloride, NaO*t*-Bu, and *i*-PrOH in THF, the former conditions gave product **1** with a 25:1 *E/Z* ratio whereas with the carbene based catalyst provides up to >99:1 *E/Z* in the product as determined by GC-MS. Further optimization of the process was thus focused on variation of the type of *N*-heterocyclic carbene (NHC) ligand (**Figure S2**).

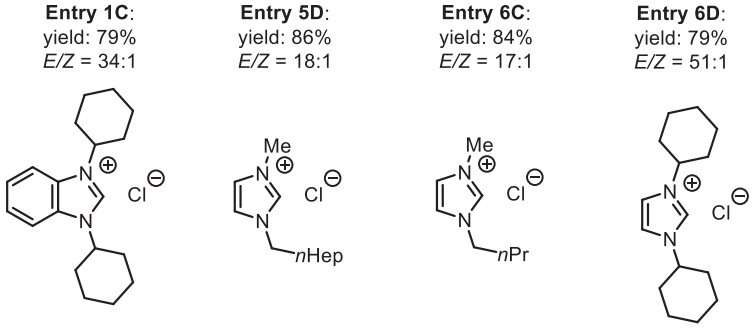


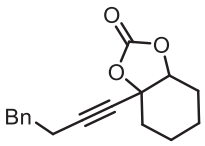
Figure S3. *E/Z* ratios using NHC-Cu catalysts that lead to a high yield of diborylated 1,3-diene **1**. The best stereoselectivity is obtained with carbene ligand “ICy" of entry **6D**.

3.5.3 Synthesis of the starting materials

Cyclic carbonates (**S1-12, S15-36**)[9] and propargylic epoxide (**S0**)[11] were prepared according to procedures reported in the literature.

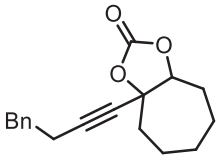
Analytical data for new alkynyl cyclic carbonates S13, S14, S37-40 and S0:

3a-(4-phenylbut-1-yn-1-yl)hexahydrobenzo[d][1,3]dioxol-2-one (**S13**)



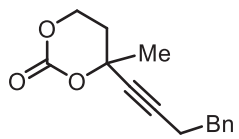
Following the **General Procedure C** described in section 2.5.3. Yellowish oil, eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.33 – 7.27 (m, 2H), 7.24 – 7.19 (m, 3H), 3.98 (dd, *J* = 12.4, 3.7 Hz, 1H), 2.85 (t, *J* = 7.2 Hz, 2H), 2.59 (t, *J* = 7.2 Hz, 2H), 2.22 – 2.15 (m, 1H), 2.08 – 2.00 (m, 1H), 1.89 (td, *J* = 12.2, 4.1 Hz, 1H), 1.82 – 1.70 (m, 3H), 1.63 – 1.49 (m, 1H), 1.43 – 1.25 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.5, 140.0, 128.5, 128.4, 126.5, 91.3, 85.2, 83.3, 75.3, 34.4, 34.1, 25.7, 23.0, 22.6, 20.8; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{17}H_{18}NaO_3$ $[M + Na]^+$ 293.1148; Found 293.1147.

3a-(4-phenylbut-1-yn-1-yl)hexahydro-4H-cyclohepta[d][1,3]dioxol-2-one (**S14**)



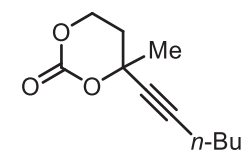
Following the **General Procedure C** described in section 2.5.3. Yellowish oil, eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.33 – 7.27 (m, 2H), 7.25 – 7.19 (m, 3H), 4.63 (dd, *J* = 10.2, 3.7 Hz, 1H), 2.84 (t, *J* = 7.3 Hz, 2H), 2.56 (t, *J* = 7.7, 7.1 Hz, 2H), 2.11 – 1.95 (m, 3H), 1.86 – 1.59 (m, 4H), 1.50 – 1.24 (m, 3H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 153.5, 140.0, 128.5, 128.4, 126.5, 88.7, 86.1, 82.1, 80.3, 36.4, 34.4, 30.2, 30.0, 23.6, 23.3, 20.8; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{18}H_{20}NaO_3$ $[M + Na]^+$ 307.1305; Found 307.1304.

4-methyl-4-(4-phenylbut-1-yn-1-yl)-1,3-dioxan-2-one (**S37**)



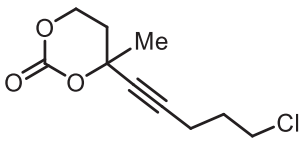
Following the **General Procedure C** described in section 2.5.3. Yellowish oil, eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.34 – 7.28 (m, 2H), 7.25 – 7.17 (m, 3H), 4.47 (ddd, *J* = 12.1, 11.0, 3.8 Hz, 1H), 4.31 (ddd, *J* = 11.0, 5.0, 2.1 Hz, 1H), 2.82 (t, *J* = 7.3 Hz, 2H), 2.53 (t, *J* = 7.1 Hz, 2H), 2.07 (ddd, *J* = 14.1, 12.1, 5.0 Hz, 1H), 1.98 (ddd, *J* = 14.1, 3.8, 2.1 Hz, 1H), 1.65 (s, 3H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 148.1, 140.0, 128.5, 126.5, 87.5, 79.1, 76.0, 65.8, 34.4, 33.8, 29.0, 20.7; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{15}H_{16}NaO_3$ $[M + Na]^+$ 267.0992; Found 267.0993.

4-(hex-1-yn-1-yl)-4-methyl-1,3-dioxan-2-one (**S38**)



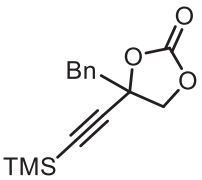
Following the **General Procedure C** described in section 2.5.3. Yellowish oil, eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 4.73 (ddd, *J* = 10.9, 5.1 Hz, 1H), 4.42 (ddd, *J* = 11.0, 4.5, 2.6 Hz, 1H), 2.22 (t, *J* = 7.0 Hz, 2H), 2.15 – 2.06 (m, 2H), 1.69 (s, 3H), 1.54 – 1.44 (m, 2H), 1.43 – 1.34 (m, 2H), 0.91 (t, *J* = 7.3 Hz, 3H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 148.2, 88.6, 78.0, 76.1, 66.0, 33.9, 30.3, 29.1, 21.9, 18.2, 13.5; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{11}H_{16}NaO_3$ $[M + Na]^+$ 219.0992; Found 219.0990.

4-(5-chloropent-1-yn-1-yl)-4-methyl-1,3-dioxan-2-one (**S39**)



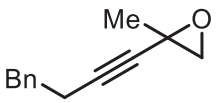
Following the **General Procedure C** described in section 2.5.3. Yellowish oil, eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 4.77 – 4.67 (m, 1H), 4.43 (ddd, *J* = 11.0, 4.5, 2.8 Hz, 1H), 3.61 (t, *J* = 6.2 Hz, 2H), 2.44 (t, *J* = 6.9 Hz, 2H), 2.16 – 2.10 (m, 2H), 2.02 – 1.92 (m, 2H), 1.70 (s, 3H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 148.1, 86.4, 79.1, 75.9, 65.9, 43.4, 33.8, 30.8, 29.1, 16.0; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{10}H_{13}ClNaO_3$ $[M + Na]^+$ 239.0445; Found 239.0457.

4-benzyl-4-((trimethylsilyl)ethynyl)-1,3-dioxolan-2-one (**S40**)



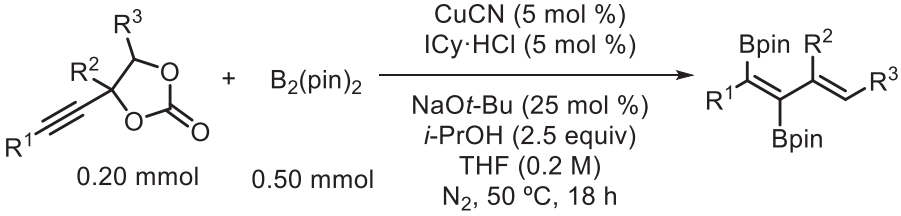
Following the **General Procedure C** described in section 2.5.3. Yellowish oil, eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (500 MHz, $CDCl_3$) δ 7.36 – 7.28 (m, 5H), 4.42 – 4.34 (m, 2H), 3.22 (s, 2H), 0.18 (s, 9H); **^{13}C NMR** (126 MHz, $CDCl_3$) δ 153.8, 132.9, 130.9, 128.9, 128.3, 100.8, 96.3, 78.5, 73.3, 45.3, -0.2; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{15}H_{18}NaO_3Si$ $[M + Na]^+$ 297.0917; Found 297.0931.

2-methyl-2-(4-phenylbut-1-yn-1-yl)oxirane (**S0**)



Prepared according to a literature procedure. The spectral data was identical to those reported in the literature.[11] **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.33 – 7.27 (m, 2H), 7.25 – 7.18 (m, 3H), 2.95 (d, *J* = 5.6 Hz, 1H), 2.82 (t, *J* = 7.6 Hz, 2H), 2.71 (d, *J* = 5.6 Hz, 1H), 2.48 (t, *J* = 7.6 Hz, 2H), 1.52 (s, 2H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 140.5, 128.5, 128.4, 126.3, 82.3, 80.3, 55.5, 47.5, 34.8, 23.2, 20.9.

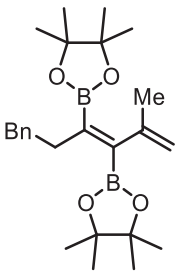
3.5.4 General procedure for the (*E*)-1,2-diborylated 1,3-dienes (1-16)



In a N_2-filled glove box, a dried 2 mL vial was charged with the respective cyclic carbonate (1.0 equiv), $B_2(pin)_2$ (2.5 equiv), NaO*t*-Bu (25 mol %), ICy·HCl (5 mol %), CuCN (5 mol %), *i*-PrOH (2.5 equiv), and THF (0.2 M). The reaction mixture was stirred for 18 h at 50 ºC. Hereafter, the solvent was evaporated by a gentle stream of N_2 and the residue was purified by flash chromatography (as indicated) on silica gel to afford the corresponding products.

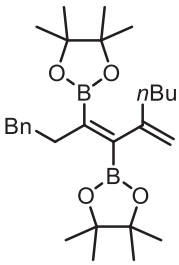
Analytical data for compounds 1-16:

(*E*)-2,2'-(2-methyl-6-phenylhexa-1,3-diene-3,4-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (**1**)[11]



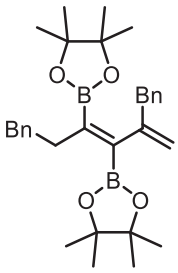
Colorless solid (61.9 mg, 73% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.31 – 7.22 (m, 4H), 7.20 – 7.14 (m, 1H), 4.73 (d, *J* = 1.2 Hz, 2H), 2.77 – 2.69 (m, 2H), 2.69 – 2.62 (m, 2H), 1.90 (d, *J* = 1.1 Hz, 3H), 1.27 (s, 12H), 1.26 (s, 12H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 150.5, 143.0, 128.5, 128.2, 125.5, 112.3, 83.2, 83.1, 37.0, 37.0, 24.8, 24.7, 23.2. The carbon centers which are directly attached to the boron atoms were not observed, most likely due to quadrupolar relaxation; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{25}H_{39}O_4{}^{10}B^{11}B$ $[M + H]^+$ 424.3065; Found 424.3066.

(*E*)-2,2'-(5-methylene-1-phenylnon-3-ene-3,4-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (**2**)



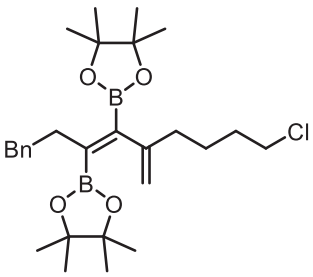
Colorless solid (69.0 mg, 74% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.33 – 7.21 (m, 4H), 7.21 – 7.14 (m, 1H), 4.82 – 4.78 (m, 1H), 4.73 – 4.71 (m, 1H), 2.77 – 2.70 (m, 2H), 2.68 – 2.61 (m, 2H), 2.22 – 2.14 (m, 2H), 1.47 – 1.33 (m, 4H), 1.26 (s, 12H), 1.26 (s, 12H), 0.92 (t, *J* = 7.2 Hz, 3H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.6, 143.0, 128.5, 128.1, 125.5, 110.6, 83.1, 37.3, 37.0, 36.0, 30.0, 24.8, 24.7, 22.6, 14.0. The carbon centers which are directly attached to the boron atoms were not observed, most likely due to quadrupolar relaxation; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{28}H_{45}O_4{}^{10}B^{11}B$ $[M + H]^+$ 466.3535; Found 466.3537.

(*E*)-2,2'-(2-benzyl-6-phenylhexa-1,3-diene-3,4-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (**3**)



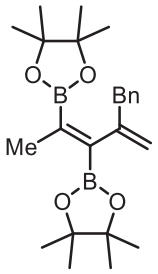
Colorless solid (68.0 mg, 68% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.33 – 7.15 (m, 10H), 4.84 (dd, *J* = 2.2, 1.2 Hz, 1H), 4.33 (q, *J* = 1.8 Hz, 1H), 3.50 (d, *J* = 1.6 Hz, 2H), 2.79 – 2.65 (m, 4H), 1.27 (s, 12H), 1.26 (s, 12H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.6, 142.9, 140.0, 130.1, 128.6, 128.2, 128.0, 125.7, 125.5, 112.3, 83.3, 83.2, 42.4, 37.0, 37.0, 24.9, 24.7. The carbon centers which are directly attached to the boron atoms were not observed, most likely due to quadrupolar relaxation; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{31}H_{43}O_4{}^{11}B_2$ $[M + H]^+$ 501.3342; Found 501.3335.

(*E*)-2,2'-(9-chloro-5-methylene-1-phenylnon-3-ene-3,4-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (**4**)



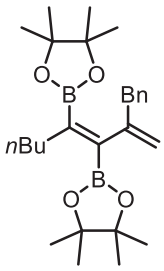
Colorless solid (74.0 mg, 74% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.31 – 7.20 (m, 4H), 7.20 – 7.14 (m, 1H), 4.83 – 4.80 (m, 1H), 4.74 – 4.70 (m, 1H), 3.55 (t, *J* = 6.9 Hz, 2H), 2.77 – 2.69 (m, 2H), 2.68 – 2.60 (m, 2H), 2.21 (t, *J* = 7.5 Hz, 2H), 1.89 – 1.79 (m, 2H), 1.64 – 1.52 (m, 2H), 1.26 (s, 12H), 1.25 (s, 12H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 153.6, 142.8, 128.6, 128.1, 125.5, 111.3, 83.2, 45.2, 37.3, 37.0, 35.4, 32.3, 25.0, 24.8, 24.7. The carbon centers which are directly attached to the boron atoms were not observed, most likely due to quadrupolar relaxation; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{28}H_{44}ClO_4{}^{10}B_2$ $[M + H]^+$ 499.3181; Found 499.3176.

(*E*)-2,2'-(4-benzylpenta-2,4-diene-2,3-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (**5**)



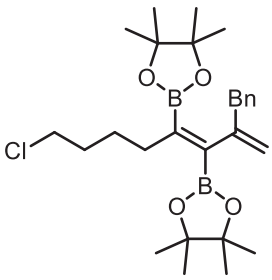
Colorless solid (45.1 mg, 55% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.31 – 7.23 (m, 4H), 7.21 – 7.15 (m, 1H), 4.84 – 4.76 (m, 1H), 4.33 – 4.27 (m, 1H), 3.47 (t, *J* = 1.6 Hz, 2H), 2.00 (s, 3H), 1.28 (s, 12H), 1.22 (s, 12H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.6, 140.0, 130.0, 128.0, 125.7, 112.2, 83.2, 42.4, 24.8, 24.6, 20.0. The carbon centers which are directly attached to the boron atoms were not observed, most likely due to quadrupolar relaxation; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{24}H_{36}NaO_4{}^{10}B^{11}B$ $[M + Na]^+$ 432.2728; Found 432.2735.

(*E*)-2,2'-(2-benzylocta-1,3-diene-3,4-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (**6**)



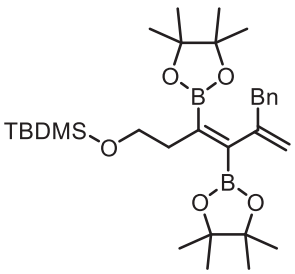
Colorless solid (68.8 mg, 76% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.32 – 7.22 (m, 4H), 7.21 – 7.16 (m, 1H), 4.84 – 4.78 (m, 1H), 4.31 – 4.25 (m, 1H), 3.47 (s, 2H), 2.43 – 2.37 (m, 2H), 1.46 – 1.32 (m, 4H), 1.27 (s, 12H), 1.23 (s, 12H), 0.92 (t, *J* = 7.1 Hz, 3H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.5, 140.0, 130.1, 127.9, 125.7, 112.1, 83.1, 42.5, 34.3, 32.5, 24.8, 24.7, 22.7, 14.0. The carbon centers which are directly attached to the boron atoms were not observed, most likely due to quadrupolar relaxation; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{27}H_{43}O_4{}^{10}B^{11}B$ $[M + H]^+$ 452.3378; Found 452.3376.

(*E*)-2,2'-(2-benzyl-8-chloroocta-1,3-diene-3,4-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (**7**)



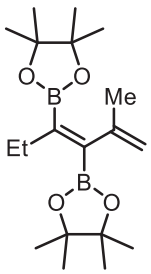
Colorless solid (68.1 mg, 70% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.30 – 7.22 (m, 4H), 7.21 – 7.15 (m, 1H), 4.83 – 4.76 (m, 1H), 4.35 – 4.29 (m, 1H), 3.56 (t, *J* = 6.8 Hz, 2H), 3.50 – 3.43 (m, 2H), 2.46 – 2.40 (m, 2H), 1.82 – 1.73 (m, 2H), 1.62 – 1.52 (m, 2H), 1.27 (s, 12H), 1.22 (s, 12H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.4, 139.9, 130.1, 128.0, 125.7, 112.3, 83.2, 83.2, 77.4, 77.0, 76.7, 45.1, 42.5, 33.5, 32.2, 27.2, 24.8, 24.7. The carbon centers which are directly attached to the boron atoms were not observed, most likely due to quadrupolar relaxation; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{27}H_{42}ClO_4{}^{10}B_2$ $[M + H]^+$ 485.3025; Found 485.3018.

(*E*)-((5-benzyl-3,4-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)hexa-3,5-dien-1-yl)-oxy)(*tert*-butyl)dimethylsilane (**8**)



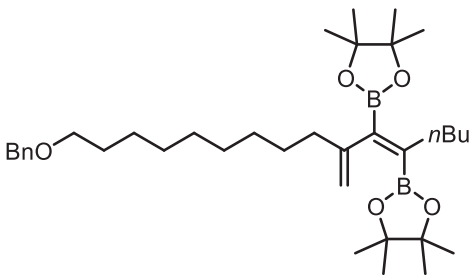
Colorless solid (47.7 mg, 43% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.31 – 7.21 (m, 4H), 7.21 – 7.15 (m, 1H), 4.82 – 4.74 (m, 1H), 4.32 – 4.22 (m, 1H), 3.69 – 3.59 (m, 2H), 3.50 – 3.42 (m, 2H), 2.72 – 2.61 (m, 2H), 1.27 (s, 12H), 1.22 (s, 12H), 0.91 (s, 9H), 0.07 (s, 6H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.5, 139.9, 130.1, 128.0, 125.7, 112.2, 83.2, 83.2, 63.4, 42.4, 38.2, 26.1, 24.8, 24.7, 18.5, -5.1. The carbon centers which are directly attached to the boron atoms were not observed, most likely due to quadrupolar relaxation; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{31}H_{52}NaO_5Si^{10}B^{11}B$ $[M + Na]^+$ 576.3699; Found 576.3693.

(*E*)-2,2'-(2-methylhexa-1,3-diene-3,4-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (**9**)



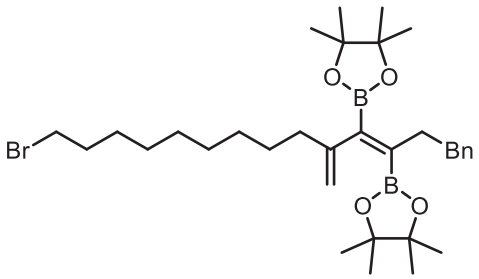
Colorless solid (45.3 mg, 65% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 4.73 – 4.64 (m, 2H), 2.37 (q, *J* = 7.5 Hz, 2H), 1.86 (t, *J* = 1.1 Hz, 3H), 1.25 (s, 12H), 1.23 (s, 12H), 1.02 (t, *J* = 7.6 Hz, 3H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 150.4, 112.2, 83.1, 83.0, 27.7, 24.7, 24.7, 23.2, 14.7. The carbon centers which are directly attached to the boron atoms were not observed, most likely due to quadrupolar relaxation; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{19}H_{35}O_4{}^{10}B^{11}B$ $[M + Na]^+$ 348.2752; Found 348.2756.

(*E*)-2,2'-(16-(benzyloxy)-7-methylenehexadec-5-ene-5,6-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (**10**)



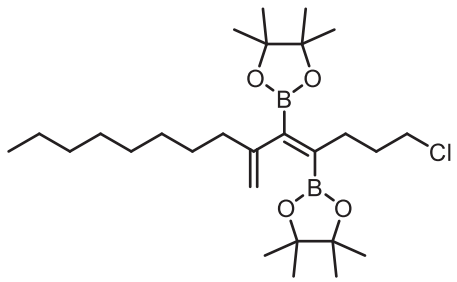
Colorless solid (60.6 mg, 51% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.34 (d, *J* = 4.4 Hz, 4H), 7.30 – 7.26 (m, 1H), 4.78 – 4.74 (m, 1H), 4.68 – 4.66 (m, 1H), 4.50 (s, 2H), 3.46 (t, *J* = 6.7 Hz, 2H), 2.38 – 2.30 (m, 2H), 2.12 (t, *J* = 7.8 Hz, 2H), 1.66 – 1.55 (m, 2H), 1.45 – 1.26 (m, 16H), 1.25 (s, 12H), 1.21 (s, 12H), 0.90 (t, *J* = 7.1 Hz, 3H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.5, 138.7, 128.3, 127.6, 127.4, 110.4, 83.0, 82.9, 72.8, 70.6, 36.4, 34.6, 32.6, 29.8, 29.6, 29.6, 29.5, 27.8, 26.2, 24.8, 24.7, 22.8, 14.0. The carbon centers which are directly attached to the boron atoms were not observed, most likely due to quadrupolar relaxation; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{36}H_{60}NaO_5{}^{10}B^{11}B$ $[M + Na]^+$ 616.4555; Found 616.4563.

(*E*)-2,2'-(14-bromo-5-methylene-1-phenyltetradec-3-ene-3,4-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (**11**)



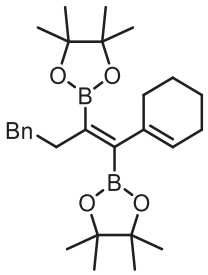
Colorless solid (73.7 mg, 60% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.32 – 7.22 (m, 4H), 7.20 – 7.14 (m, 1H), 4.82 – 4.77 (m, 1H), 4.74 – 4.69 (m, 1H), 3.41 (t, *J* = 6.9 Hz, 2H), 2.80 – 2.69 (m, 2H), 2.69 – 2.60 (m, 2H), 2.20 – 2.13 (m, 2H), 1.92 – 1.81 (m, 2H), 1.50 – 1.40 (m, 4H), 1.32 (s, 8H), 1.26 (s, 12H), 1.25 (s, 12H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.5, 142.9, 128.5, 128.2, 125.5, 110.6, 83.1, 37.3, 37.0, 36.4, 34.0, 32.9, 29.5, 29.5, 28.8, 28.2, 27.8, 24.8, 24.7. The carbon centers which are directly attached to the boron atoms were not observed, most likely due to quadrupolar relaxation; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{33}H_{54}BrO_4{}^{11}B_2$ $[M + H]^+$ 615.3386; Found 615.3397.

(*E*)-2,2'-(1-chloro-6-methylenetetradec-4-ene-4,5-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (**12**)



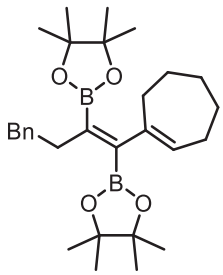
Colorless solid (59.3 mg, 60% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz $CDCl_3$) δ 4.76 – 4.72 (m, 1H), 4.69 – 4.66 (m, 1H), 3.53 (t, *J* = 7.0 Hz, 2H), 2.41 – 2.51 (m, 2H), 2.11 (t, *J* = 7.7 Hz, 2H), 1.95 – 1.85 (m, 2H), 1.35 – 1.45 (m, 2H), 1.25 – 1.33 (m, 10H), 1.25 (s, 12H), 1.21 (s, 12H), 0.91 – 0.83 (m, 3H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.4, 110.6, 83.2, 83.1, 45.1, 36.3, 33.3, 32.1, 31.9, 29.5, 29.5, 29.3, 27.8, 24.8, 24.7, 22.7, 14.1. The carbon centers which are directly attached to the boron atoms were not observed, most likely due to quadrupolar relaxation; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{27}H_{50}ClO_4{}^{11}B_2$ $[M + H]^+$ 495.3578; Found 495.3580.

(*E*)-2,2'-(1-(cyclohex-1-en-1-yl)-4-phenylbut-1-ene-1,2-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (**13**)



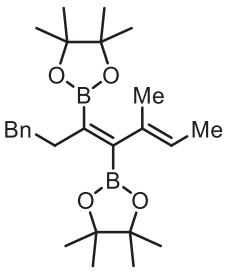
Colorless solid (14.9 mg, 16% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.29 – 7.13 (m, 5H), 5.41 – 5.35 (m, 1H), 2.75 – 2.66 (m, 2H), 2.62 – 2.53 (m, 2H), 2.16 – 2.06 (m, 2H), 2.06 – 1.99 (m, 2H), 1.67 – 1.59 (m, 2H), 1.57 – 1.52 (m, 2H), 1.26 (s, 12H), 1.24 (s, 12H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 143.9, 143.1, 128.5, 128.1, 125.5, 122.2, 83.0, 37.5, 37.1, 28.9, 25.5, 24.9, 24.8, 22.8, 22.2. The carbon centers which are directly attached to the boron atoms were not observed, most likely due to quadrupolar relaxation; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{28}H_{43}O_4{}^{11}B_2$ $[M + H]^+$ 465.3342; Found 465.3342.

(*E*)-2,2'-(1-(cyclohept-1-en-1-yl)-4-phenylbut-1-ene-1,2-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (**14**)



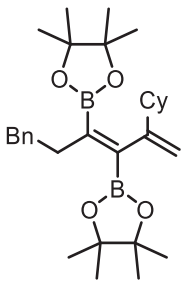
Colorless solid (14.4 mg, 15% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.28 – 7.14 (m, 5H), 5.58 (t, J = 6.4 Hz, 1H), 2.74 – 2.68 (m, 2H), 2.58 – 2.52 (m, 2H), 2.24 – 2.19 (m, 2H), 2.13 – 2.07 (m, 2H), 1.77 – 1.71 (m, 2H), 1.63 – 1.58 (m, 2H), 1.56 – 1.49 (m, 2H), 1.26 (s, 12H), 1.25 (s, 12H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 150.3, 143.2, 128.5, 128.1, 127.3, 125.5, 83.1, 83.1, 37.5, 37.2, 33.6, 32.8, 29.1, 26.9, 26.7, 24.9, 24.8. The carbon centers which are directly attached to the boron atoms were not observed, most likely due to quadrupolar relaxation; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{29}H_{45}O_4{}^{10}B_2$ $[M + H]^+$ 477.3571; Found 477.3568.

2,2'-((3*E*,5*E*)-5-methyl-1-phenylhepta-3,5-diene-3,4-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (**15**)



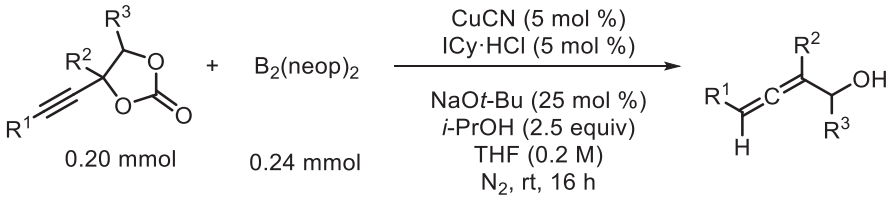
Colorless solid (25.4 mg, 29% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.29 – 7.14 (m, 5H), 5.26 – 5.17 (m, 1H), 2.74 – 2.68 (m, 2H), 2.63 – 2.57 (m, 2H), 1.76 – 1.71 (m, 3H), 1.62 – 1.56 (m, 3H), 1.25 (s, 12H), 1.24 (s, 12H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 143.1, 142.1, 128.5, 128.1, 125.5, 120.1, 83.1, 83.0, 37.3, 37.1, 24.8, 24.8, 16.6, 13.8. The carbon centers which are directly attached to the boron atoms were not observed, most likely due to quadrupolar relaxation; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{26}H_{41}O_4{}^{11}B_2$ $[M + H]^+$ 439.3185 Found 439.3185.

(*E*)-2,2'-(2-cyclohexyl-6-phenylhexa-1,3-diene-3,4-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (**16**)



Colorless solid (24.6 mg, 25% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.29 – 7.14 (m, 5H), 4.84 – 4.80 (m, 1H), 4.71 – 4.67 (m, 1H), 2.76 – 2.70 (m, 2H), 2.65 – 2.58 (m, 2H), 2.03 – 1.87 (m, 3H), 1.81 – 1.63 (m, 3H), 1.25 (s, 12H), 1.25 (s, 12H), 1.20 – 1.06 (m, 5H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 159.1, 143.0, 128.5, 128.1, 125.5, 109.0, 83.2, 83.1, 43.2, 37.4, 37.0, 32.4, 27.0, 26.5, 24.8, 24.7. The carbon centers which are directly attached to the boron atoms were not observed, most likely due to quadrupolar relaxation; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{30}H_{47}O_4{}^{11}B_2$ $[M + H]^+$ 493.3655; Found 493.3661.

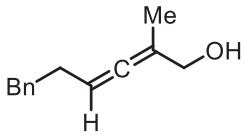
3.5.5 General procedure for the synthesis of α-hydroxyallenes (17-39)



In a N_2-filled glove box, a dried 2 mL vial was charged with the respective cyclic carbonate (1.0 equiv), $B_2(neop)_2$ (1.2 equiv), NaO*t*-Bu (25 mol %), ICy·HCl (5 mol %), CuCN (5 mol %), *i*-PrOH (2.5 equiv) and THF (0.2 M as final concentration). The reaction mixture was stirred for 16 h at r.t. Hereafter, the solvent was evaporated by a gentle stream of N_2 and the residue was purified by flash chromatography on silica gel (eluent indicated per case) to afford the corresponding products.

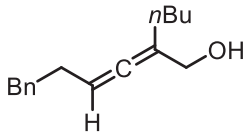
Analytical data for compounds 17-39:

2-methyl-6-phenylhexa-2,3-dien-1-ol (**17**)



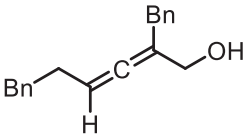
Colorless oil (24.9 mg, 66% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.33 – 7.27 (m, 2H), 7.24 – 7.16 (m, 3H), 5.35 – 5.24 (m, 1H), 3.91 – 3.83 (m, 2H), 2.82 – 2.68 (m, 2H), 2.46 – 2.29 (m, 2H), 1.64 (d, *J* = 2.9 Hz, 3H), 1.20 (s, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 199.7, 141.6, 128.5, 128.3, 125.9, 101.0, 93.3, 63.8, 35.1, 30.4, 15.6; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{13}H_{16}NaO$ $[M + Na]^+$ 211.1093; Found 211.1088.

2-butyl-6-phenylhexa-2,3-dien-1-ol (**18**)



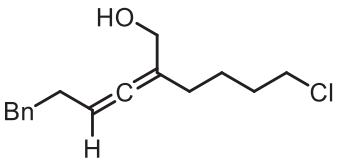
Colorless oil (33.2 mg, 72% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.34 – 7.27 (m, 2H), 7.23 – 7.16 (m, 3H), 5.40 – 5.32 (m, 1H), 3.94 – 3.85 (m, 2H), 2.82 – 2.68 (m, 2H), 2.48 – 2.29 (m, 2H), 1.96 – 1.87 (m, 2H), 1.44 – 1.28 (m, 4H), 1.26 – 1.15 (m, 1H), 0.95 – 0.84 (m, 3H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 199.2, 141.6, 128.5, 128.3, 125.9, 106.2, 94.6, 63.0, 35.3, 30.6, 29.8, 29.0, 22.4, 13.9; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{16}H_{22}NaO$ $[M + Na]^+$ 253.1563; Found 253.1569.

2-benzyl-6-phenylhexa-2,3-dien-1-ol (**19**)



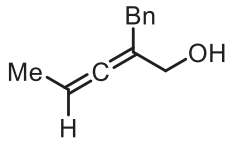
Colorless oil (31.2 mg, 59% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.33 – 7.27 (m, 4H), 7.25 – 7.14 (m, 6H), 5.38 – 5.30 (m, 1H), 3.96 – 3.86 (m, 2H), 3.30 (d, J = 2.5 Hz, 2H), 2.73 – 2.63 (m, 2H), 2.42 – 2.26 (m, 2H), 1.31 – 1.14 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 200.6, 141.6, 139.2, 128.9, 128.5, 128.3, 128.3, 126.3, 126.0, 105.5, 94.2, 62.5, 36.6, 35.2, 30.5; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{19}H_{20}NaO$ $[M + Na]^+$ 287.1406; Found 287.1419.

2-(4-chlorobutyl)-6-phenylhexa-2,3-dien-1-ol (**20**)



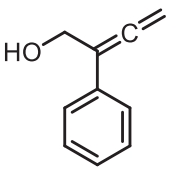
Colorless oil (38.1 mg, 72% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.33 – 7.27 (m, 2H), 7.23 – 7.17 (m, 3H), 5.40 – 5.33 (m, 1H), 3.89 (t, J = 2.4 Hz, 2H), 3.52 (t, J = 6.7 Hz, 2H), 2.79 – 2.71 (m, 2H), 2.46 – 2.33 (m, 2H), 1.98 – 1.91 (m, 2H), 1.83 – 1.74 (m, 2H), 1.56 – 1.46 (m, 2H), 1.21 (s, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 199.4, 141.5, 128.5, 128.3, 126.0, 105.4, 94.8, 63.0, 44.9, 35.2, 32.2, 30.5, 28.4, 24.8; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{16}H_{21}ClNaO$ $[M + Na]^+$ 287.1173; Found 287.1165.

2-benzylpenta-2,3-dien-1-ol (**21a**)



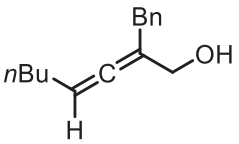
Colorless oil (20.9 mg, 60% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.32 – 7.26 (m, 2H), 7.25 – 7.18 (m, 3H), 5.36 – 5.22 (m, 1H), 4.07 – 3.94 (m, 2H), 3.36 (d, *J* = 2.4 Hz, 2H), 1.67 (d, *J* = 7.0 Hz, 3H), 1.62 – 1.48 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 201.1, 139.3, 128.8, 128.3, 126.3, 104.3, 89.6, 62.5, 36.7, 14.7; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{12}H_{13}$ $[M - OH]^+$ 157.1012; Found 157.1009.

2-phenylbuta-2,3-dien-1-ol (**21b**)[20]



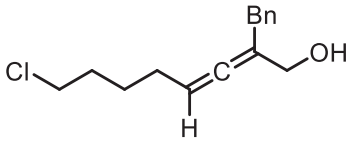
Yellowish oil (14.0 mg, 48% yield). Eluent 2-5 % EtOAc/hexanes. The spectral data was identical to those reported in the literature. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.46 – 7.41 (m, 2H), 7.38 – 7.32 (m, 2H), 7.27 – 7.22 (m, 1H), 5.25 (t, *J* = 2.7 Hz, 2H), 4.58 (t, *J* = 2.7 Hz, 2H), 1.71 (s, 1H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 207.6, 133.8, 128.6, 127.2, 126.1, 106.0, 80.3, 61.5.

2-benzylocta-2,3-dien-1-ol (**22**)



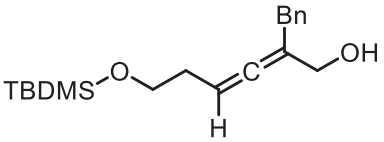
Colorless oil (25.1 mg, 58% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.33 – 7.26 (m, 2H), 7.25 – 7.18 (m, 3H), 5.35 – 5.26 (m, 1H), 4.01 (t, *J* = 2.7 Hz, 2H), 3.36 (d, *J* = 2.5 Hz, 2H), 2.05 – 1.95 (m, 2H), 1.54 – 1.45 (m, 1H), 1.39 – 1.25 (m, 4H), 0.95 – 0.82 (m, 3H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 200.2, 139.3, 128.9, 128.3, 126.3, 104.8, 95.2, 62.6, 36.7, 31.4, 28.8, 22.1, 13.9; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{15}H_{20}NaO$ $[M + Na]^+$ 239.1406; Found 239.1401.

2-benzyl-8-chloroocta-2,3-dien-1-ol (**23**)



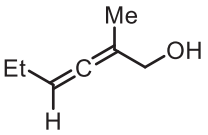
Colorless oil (26.1 mg, 52% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.32 – 7.26 (m, 2H), 7.24 – 7.18 (m, 3H), 5.35 – 5.22 (m, 1H), 4.08 – 3.96 (m, 2H), 3.50 (t, *J* = 6.6 Hz, 2H), 3.36 (d, *J* = 2.6 Hz, 2H), 2.08 – 1.95 (m, 2H), 1.78 – 1.68 (m, 2H), 1.60 – 1.54 (m, 1H), 1.53 – 1.44 (m, 2H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 200.5, 139.1, 128.9, 128.3, 126.3, 105.4, 94.4, 62.7, 44.9, 36.6, 31.8, 28.2, 26.3; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{15}H_{19}ClNaO$ $[M + Na]^+$ 273.1017; Found 273.1009.

2-benzyl-6-((*tert*-butyldimethylsilyl)oxy)hexa-2,3-dien-1-ol (**24**)



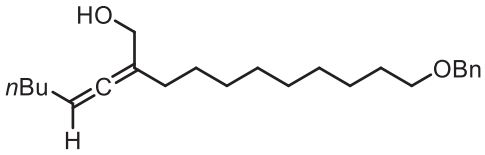
Colorless oil (28.0 mg, 44% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.31 – 7.26 (m, 2H), 7.24 – 7.18 (m, 3H), 5.37 – 5.30 (m, 1H), 4.00 (d, *J* = 3.1 Hz, 2H), 3.70 – 3.56 (m, 2H), 3.39 – 3.29 (m, 2H), 2.25 – 2.14 (m, 2H), 1.84 (s, 1H), 0.89 (s, 9H), 0.06 (s, 3H), 0.06 (s, 3H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 200.7, 139.2, 128.8, 128.3, 126.3, 105.4, 92.0, 62.6, 62.1, 36.5, 32.6, 26.0, 18.4, -5.2, -5.3; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{19}H_{30}NaO_2Si$ $[M + Na]^+$ 341.1907; Found 341.1902.

2-methylhexa-2,3-dien-1-ol (**25**)[21]



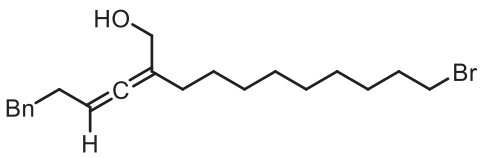
Colorless oil (11.2 mg, 50% yield). Eluent 2-5 % EtOAc/hexanes. Note: this compound was previously reported. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 5.42 – 5.33 (m, 1H), 4.05 – 3.97 (m, 2H), 2.09 – 2.00 (m, 2H), 1.76 – 1.71 (m, 3H), 1.57 (s, 1H), 1.02 (t, *J* = 7.4 Hz, 3H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 198.7, 101.3, 96.3, 63.9, 22.3, 15.8, 13.5.

11-(benzyloxy)-2-(hex-1-en-1-ylidene)undecan-1-ol (**26**)



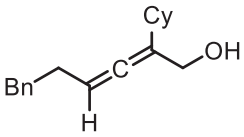
Colorless oil (48.0 mg, 67% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.37 – 7.32 (m, 4H), 7.30 – 7.25 (m, 1H), 5.38 – 5.28 (m, 1H), 4.50 (s, 2H), 4.05 – 3.94 (m, 2H), 3.46 (t, *J* = 6.6 Hz, 2H), 2.07 – 1.99 (m, 2H), 1.99 – 1.93 (m, 2H), 1.66 – 1.56 (m, 3H), 1.46 – 1.26 (m, 16H), 0.94 – 0.87 (m, 3H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 198.8, 138.7, 128.3, 127.6, 127.5, 105.7, 95.7, 72.9, 70.5, 63.1, 31.5, 29.8, 29.6, 29.5, 29.4, 29.4, 29.3, 29.0, 27.7, 26.2, 22.2, 13.9; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{24}H_{38}NaO_2$ [M + Na]$^+$ 381.2764; Found 381.2752.

11-bromo-2-(4-phenylbut-1-en-1-ylidene)undecan-1-ol (**27**)



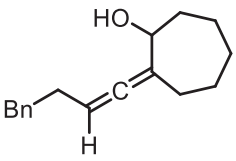
Colorless oil (54.6 mg, 72% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.33 – 7.27 (m, 2H), 7.23 – 7.17 (m, 3H), 5.40 – 5.32 (m, 1H), 3.94 – 3.85 (m, 2H), 3.40 (t, *J* = 6.9 Hz, 2H), 2.82 – 2.67 (m, 2H), 2.46 – 2.28 (m, 2H), 1.97 – 1.89 (m, 2H), 1.88 – 1.80 (m, 2H), 1.47 – 1.35 (m, 2H), 1.34 – 1.25 (m, 10H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 199.2, 141.6, 128.5, 128.3, 126.0, 106.2, 94.6, 63.0, 35.3, 34.0, 32.8, 30.6, 29.4, 29.4, 29.3, 29.3, 28.8, 28.2, 27.6; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{21}H_{31}BrNaO$ [M + Na]$^+$ 401.1450; Found 401.1466.

2-cyclohexyl-6-phenylhexa-2,3-dien-1-ol (**28**)



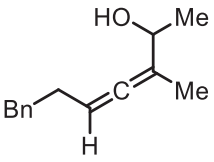
Colorless oil (34.9 mg, 68% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.33 – 7.27 (m, 2H), 7.23 – 7.16 (m, 3H), 5.46 – 5.35 (m, 1H), 4.01 – 3.88 (m, 2H), 2.75 (t, *J* = 7.4 Hz, 2H), 2.45 – 2.31 (m, 2H), 1.82 – 1.69 (m, 5H), 1.68 – 1.62 (m, 1H), 1.29 – 1.03 (m, 6H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 198.7, 141.6, 128.5, 128.3, 125.9, 112.0, 95.6, 61.7, 37.9, 35.2, 32.5, 32.3, 30.7, 26.4, 26.4, 26.2; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{18}H_{24}NaO$ $[M + Na]^+$ 279.1719; Found 279.1716.

2-(4-phenylbut-1-en-1-ylidene)cycloheptan-1-ol (**29**)



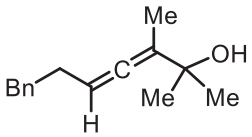
Colorless oil (28.1 mg, 58% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.33 – 7.27 (m, 2H), 7.24 – 7.17 (m, 3H), 5.39 – 5.28 (m, 1H), 4.19 – 4.07 (m, 1H), 2.86 – 2.69 (m, 2H), 2.44 – 2.30 (m, 2H), 2.26 – 2.17 (m, 1H), 2.11 – 2.01 (m, 1H), 2.00 – 1.90 (m, 1H), 1.69 – 1.44 (m, 7H), 1.40 – 1.31 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 200.4, 141.6, 128.5, 128.3, 126.0, 110.3, 93.5, 71.6, 36.7, 35.3, 30.8, 29.2, 29.1, 29.0, 23.8; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{17}H_{22}NaO$ $[M + Na]^+$ 265.1563; Found 265.1562.

3-methyl-7-phenylhepta-3,4-dien-2-ol (**30**)



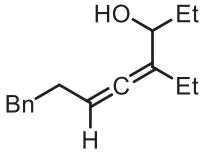
Colorless oil (27.1 mg, 67% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.32 – 7.27 (m, 2H), 7.22 – 7.17 (m, 3H), 5.32 – 5.23 (m, 1H), 4.10 – 4.00 (m, 1H), 2.81 – 2.67 (m, 2H), 2.44 – 2.27 (m, 2H), 1.68 – 1.61 (m, 3H), 1.47 – 1.41 (m, 1H), 1.21 (d, *J* = 6.4 Hz, 3H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 199.3, 141.7, 128.5, 128.3, 125.9, 105.0, 93.1, 68.5, 35.2, 30.5, 21.9, 15.1; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{14}H_{18}NaO$ $[M + Na]^+$ 225.1250; Found 225.1249.

2,3-dimethyl-7-phenylhepta-3,4-dien-2-ol (**31**)



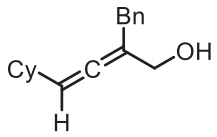
Colorless oil (32.9 mg, 76% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.32 – 7.27 (m, 2H), 7.23 – 7.17 (m, 3H), 5.29 – 5.21 (m, 1H), 2.79 – 2.68 (m, 2H), 2.42 – 2.29 (m, 2H), 1.69 (d, *J* = 2.9 Hz, 3H), 1.53 (s, 1H), 1.28 (s, 3H), 1.28 (s, 3H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 198.9, 141.7, 128.5, 128.4, 125.9, 108.2, 92.7, 70.8, 35.2, 30.6, 28.8, 28.6, 14.9; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{15}H_{20}NaO$ $[M + Na]^+$ 239.1406; Found 239.1403.

4-ethyl-8-phenylocta-4,5-dien-3-ol (**32**)



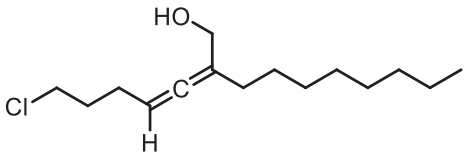
Colorless oil (34.1 mg, 74% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.33 – 7.27 (m, 2H), 7.23 – 7.17 (m, 3H), 5.47 – 5.33 (m, 1H), 3.92 – 3.82 (m, 1H), 2.79 – 2.69 (m, 2H), 2.45 – 2.29 (m, 2H), 2.00 – 1.87 (m, 2H), 1.68 – 1.56 (m, 1H), 1.50 – 1.36 (m, 2H), 1.00 – 0.95 (m, 3H), 0.89 (t, *J* = 7.4 Hz, 3H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 199.2, 141.7, 128.5, 128.3, 125.9, 110.7, 95.4, 73.1, 35.5, 31.0, 28.4, 21.7, 12.3, 9.5; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{16}H_{22}NaO$ $[M + Na]^+$ 253.1563; Found 253.1566.

2-benzyl-4-cyclohexylbuta-2,3-dien-1-ol (**33**)



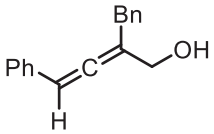
Colorless oil (33.0 mg, 68% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.31 – 7.26 (m, 2H), 7.25 – 7.18 (m, 3H), 5.35 – 5.25 (m, 1H), 4.01 (t, *J* = 2.6 Hz, 2H), 3.36 (d, *J* = 2.6 Hz, 2H), 2.00 – 1.89 (m, 1H), 1.76 – 1.58 (m, 5H), 1.52 (s, 1H), 1.33 – 1.11 (m, 3H), 1.07 – 0.94 (m, 2H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 198.9, 139.2, 129.0, 128.3, 126.2, 105.9, 101.5, 62.6, 37.5, 36.8, 33.2, 33.0, 26.1, 26.0; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{17}H_{22}NaO$ $[M + Na]^+$ 265.1563; Found 265.1560.

2-(5-chloropent-1-en-1-ylidene)decan-1-ol (**34**)



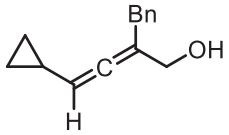
Colorless oil (36.2 mg, 70% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 5.34 – 5.27 (m, 1H), 4.06 – 3.97 (m, 2H), 3.58 (t, *J* = 6.6 Hz, 2H), 2.21 – 2.13 (m, 2H), 2.00 – 1.94 (m, 2H), 1.92 – 1.83 (m, 2H), 1.58 (s, 1H), 1.47 – 1.37 (m, 2H), 1.34 – 1.22 (m, 10H), 0.91 – 0.83 (m, 3H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 199.4, 106.6, 93.7, 63.1, 44.3, 31.9, 31.8, 29.4, 29.4, 29.3, 29.3, 27.7, 26.3, 22.7, 14.1; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{15}H_{27}ClNaO$ $[M + Na]^+$ 281.1643; Found 281.1654.

2-benzyl-4-phenylbuta-2,3-dien-1-ol (**35**)



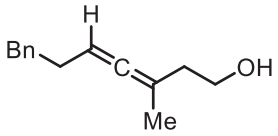
Colorless oil (40.2 mg, 85% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.34 – 7.29 (m, 8H), 7.27 – 7.21 (m, 2H), 6.39 – 6.32 (m, 1H), 4.23 – 4.11 (m, 2H), 3.53 (d, *J* = 2.4 Hz, 2H), 1.67 (s, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 201.8, 138.8, 134.5, 129.0, 128.7, 128.5, 127.2, 126.8, 126.6, 109.0, 97.8, 62.4, 36.7; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{17}H_{16}NaO$ $[M + Na]^+$ 259.1093; Found 259.1088.

2-benzyl-4-cyclopropylbuta-2,3-dien-1-ol (**36**)



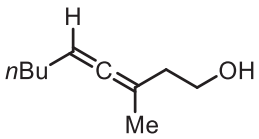
Colorless oil (20.0 mg, 50% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.32 – 7.26 (m, 2H), 7.24 – 7.18 (m, 3H), 5.28 – 5.16 (m, 1H), 4.07 – 3.94 (m, 2H), 3.36 (d, *J* = 2.4 Hz, 2H), 1.52 (s, 1H), 1.29 – 1.18 (m, 1H), 0.70 – 0.67 (m, 1H), 0.67 – 0.65 (m, 1H), 0.35 – 0.29 (m, 1H), 0.26 – 0.20 (m, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 199.3, 139.1, 128.9, 128.3, 126.3, 106.9, 99.7, 62.4, 36.8, 9.7, 7.2, 6.8; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{14}H_{16}NaO$ $[M + Na]^+$ 223.1093; Found 223.1091.

3-methyl-7-phenylhepta-3,4-dien-1-ol (**37**)



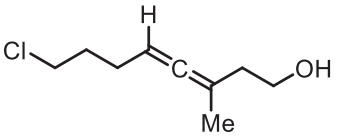
Colorless oil (36.0 mg, 89% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.31 – 7.26 (m, 2H), 7.22 – 7.16 (m, 3H), 5.20 – 5.08 (m, 1H), 3.63 (t, *J* = 6.1 Hz, 2H), 2.77 – 2.69 (m, 2H), 2.38 – 2.27 (m, 2H), 2.18 – 2.11 (m, 2H), 1.68 – 1.63 (m, 3H), 1.60 (s, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 201.4, 141.8, 128.5, 128.3, 125.8, 96.7, 90.5, 60.7, 37.1, 35.5, 30.9, 19.4; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{14}H_{18}NaO$ $[M + Na]^+$ 225.1250; Found 225.1243.

3-methylnona-3,4-dien-1-ol (**38**)



Colorless oil (19.1 mg, 62% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 5.14 – 5.05 (m, 1H), 3.72 (t, *J* = 6.1 Hz, 2H), 2.22 – 2.16 (m, 2H), 2.01 – 1.93 (m, 2H), 1.86 – 1.75 (m, 1H), 1.72 – 1.66 (m, 3H), 1.40 – 1.29 (m, 4H), 0.92 – 0.85 (m, 3H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 201.1, 96.1, 91.3, 60.8, 37.1, 31.4, 29.0, 22.2, 19.5, 13.9; **HRMS** (APCI/TOF) *m/z* Calcd for $C_{10}H_{19}O$ $[M + H]^+$ 155.1430; Found 155.1429.

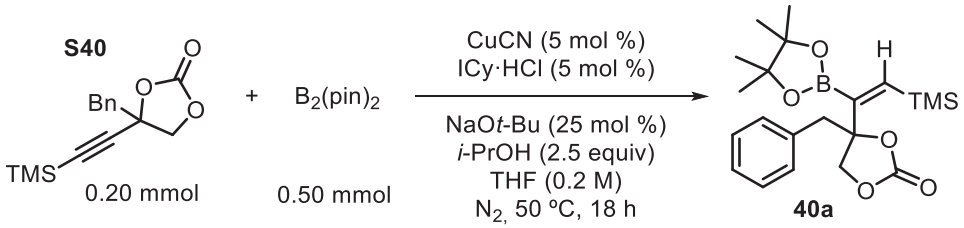
8-chloro-3-methylocta-3,4-dien-1-ol (**39**)



Colorless oil (25.4 mg, 73% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 5.14 – 5.03 (m, 1H), 3.72 (t, *J* = 6.2 Hz, 2H), 3.57 (t, *J* = 6.6 Hz, 2H), 2.24 – 2.18 (m, 2H), 2.17 – 2.10 (m, 2H), 1.92 – 1.83 (m, 2H), 1.71 (d, *J* = 2.9 Hz, 3H), 1.61 (s, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 201.6, 97.0, 89.5, 60.7, 44.3, 37.2, 31.8, 26.4, 19.4; **HRMS** (APCI/TOF) *m/z* Calcd for $C_9H_{16}ClO$ $[M + H]^+$ 175.0884; Found 175.0884.

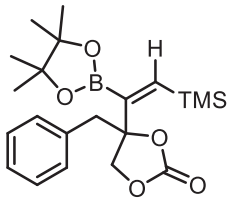
3.5.6 Competition experiments, scale-up, post-modifications and MS data

Procedure for the synthesis of compound 40a:



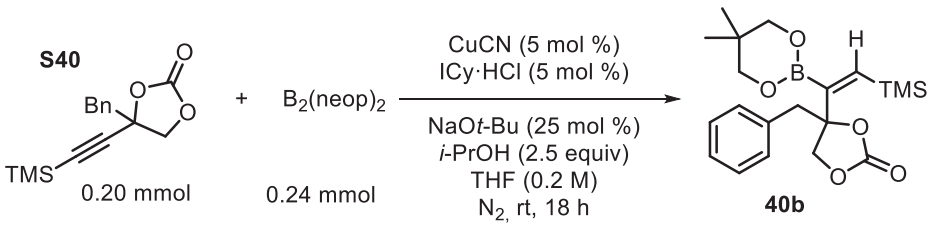
In a N_2-filled glove box, a dried 2 mL vial was charged with cyclic carbonate **S40** (54.9 mg, 0.20 mmol, 1.0 equiv), $B_2(pin)_2$ (128.3 mg, 0.50 mmol, 2.5 equiv), NaO*t*-Bu (5.0 mg, 0.05 mmol, 25 mol %), ICy·HCl (2.7 mg, 0.01 mmol, 5 mol %), CuCN (0.9 mg, 0.01 mmol, 5 mol %), *i*-PrOH (30.2 mg, 0.50 mmol, 2.5 equiv) and THF (1 mL, 0.2 M as final concentration). The reaction mixture was stirred for 18 h at 50 ºC. Hereafter, the solvent was evaporated by a gentle stream of N_2 and the residue was purified by flash chromatography, and the so obtained product crystallized from a concentrated ethyl acetate solution.

(*Z*)-4-benzyl-4-(1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-2-(trimethylsilyl)vinyl)-1,3-dioxolan-2-one (**40a**)



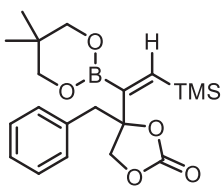
Colorless solid (24.9 mg, 31% yield). Eluent 1-3 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.37 – 7.27 (m, 3H), 7.25 – 7.20 (m, 2H), 6.80 (s, 1H), 4.54 (d, J = 9.0 Hz, 1H), 4.13 (d, J = 9.0 Hz, 1H), 3.08 (q, J = 14.2 Hz, 2H), 1.31 (s, 6H), 1.30 (s, 6H), 0.16 (s, 9H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 153.8, 150.5, 134.0, 130.5, 128.6, 127.6, 88.5, 84.4, 72.7, 44.7, 24.8, 24.7, 0.5. Carbon directly attached to the boron atom was not observed, most likely due to quadrupolar relaxation; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{21}H_{31}NaO_5Si^{10}B$ $[M + Na]^+$ 424.1962; Found 424.1956.

Procedure for the synthesis of compound 40b:



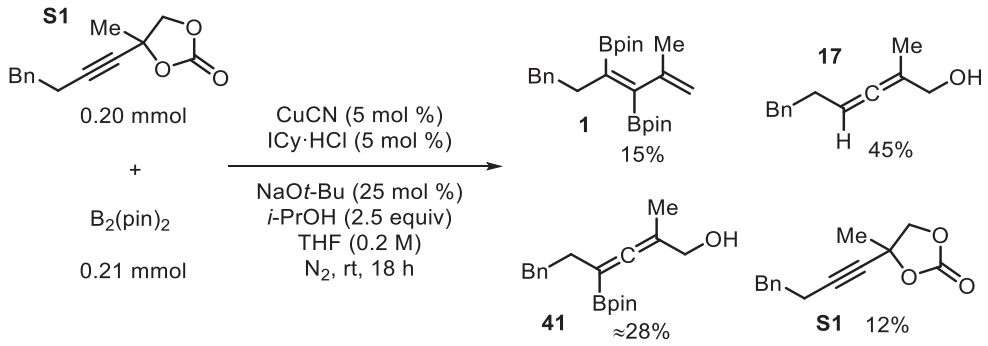
In a N_2-filled glove box, a dried 2 mL vial was charged with cyclic carbonate **S40** (54.9 mg, 0.20 mmol, 1.0 equiv), $B_2(neop)_2$ (55.9 mg, 0.24 mmol, 2.5 equiv), NaO*t*-Bu (5.0 mg, 0.05 mmol, 25 mol %), ICy·HCl (2.7 mg, 0.01 mmol, 5 mol %), CuCN (0.9 mg, 0.01 mmol, 5 mol %), *i*-PrOH (30.2 mg, 0.50 mmol, 2.5 equiv) and THF (1 mL, 0.2 M as final concentration). The reaction mixture was stirred for 18 h at rt. Hereafter, the solvent was evaporated by a gentle stream of N_2 and the residue was purified by flash chromatography (Note: it would be better to use the GC or LC to confirm which tubes contain the product).

(*Z*)-4-benzyl-4-(1-(5,5-dimethyl-1,3,2-dioxaborinan-2-yl)-2-(trimethylsilyl)vinyl)-1,3-dioxolan-2-one (**40b**)



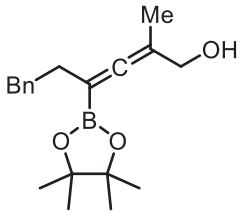
White solid (33.2 mg, 43% yield). Eluent 1-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.36 – 7.27 (m, 3H), 7.26 – 7.22 (m, 2H), 6.77 (s, 1H), 4.53 (d, J = 9.1 Hz, 1H), 4.12 (d, J = 9.1 Hz, 1H), 3.68 (s, 4H), 3.08 (s, 2H), 1.00 (s, 6H), 0.17 (s, 9H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 153.9, 147.5, 134.2, 130.6, 128.6, 127.5, 89.0, 72.9, 72.4, 44.8, 31.7, 21.8, 0.7. Carbon directly attached to the boron atom was not observed, most likely due to quadrupolar relaxation; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{20}H_{29}NaO_5Si^{11}B$ $[M + Na]^+$ 411.1770; Found 411.1765.

Procedure leading to a mixture of products:



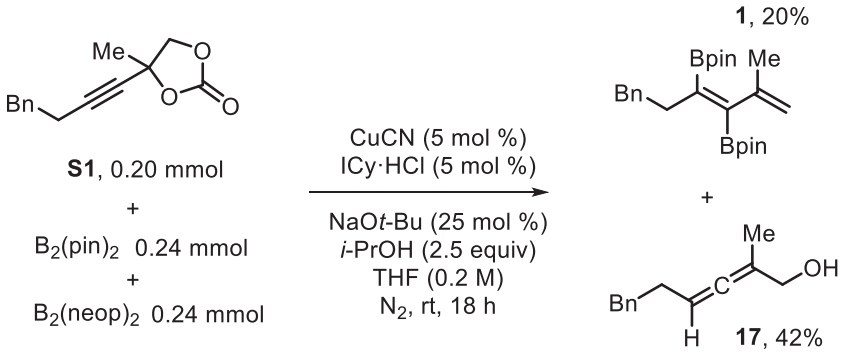
In a N_2-filled glove box, a dried 2 mL vial was charged with cyclic carbonate **S1** (46.1 mg, 0.20 mmol, 1.0 equiv), $B_2(pin)_2$ (53.9 mg, 0.21 mmol, 1.05 equiv), NaO*t*-Bu (5.0 mg, 0.05 mmol, 25 mol %), ICy·HCl (2.7 mg, 0.01 mmol, 5 mol %), CuCN (0.9 mg, 0.01 mmol, 5 mol %), *i*-PrOH (30.2 mg, 0.50 mmol, 2.5 equiv), and THF (1 mL, 0.2 M as final concentration). The reaction mixture was stirred for 18 h at room temperature. Hereafter, the solvent was evaporated by a gentle stream of N_2 and the residue was purified by flash chromatography (Eluent 2-50 % EtOAc/hexanes) on silica gel to afford the corresponding products **1**, **17** and **41**.

2-methyl-6-phenyl-4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)hexa-2,3-dien-1-ol (**41**)



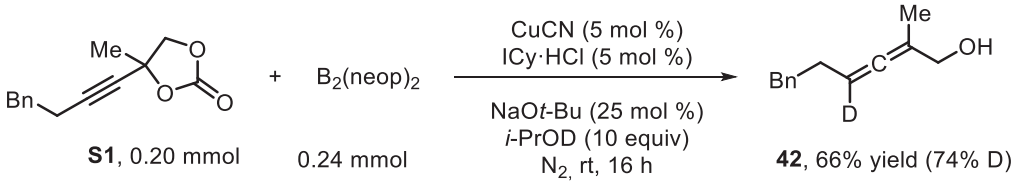
This compound was separated during the screening of optimal reaction condition. The spectral data was identical with those reported in the literature,[16] the NMR spectra of **41** are provided in section 9 of this document. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.29 – 7.23 (m, 2H), 7.20 – 7.15 (m, 3H), 3.88 (q, *J* = 12.3 Hz, 2H), 2.78 – 2.70 (m, 2H), 2.46 – 2.32 (m, 2H), 1.92 (s, 1H), 1.64 (s, 3H), 1.26 (s, 12H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 209.2, 142.1, 128.6, 128.1, 125.7, 97.0, 83.6, 64.3, 35.3, 31.5, 24.8, 24.7, 15.1. Carbons which are directly attached to the boron atoms were not observed most likely due to quadrupolar relaxation.

Competition experiment:



In a N_2-filled glove box, a dried 2 mL vial was charged with cyclic carbonate **S1** (46.1 mg, 0.20 mmol, 1.0 equiv), $B_2(pin)_2$ (61.6 mg, 0.24 mmol, 1.2 equiv), $B_2(neop)_2$ (55.9 mg, 0.24 mmol, 1.2 equiv), NaO*t*-Bu (5.0 mg, 0.05 mmol, 25 mol %), ICy·HCl (2.7 mg, 0.01 mmol, 5 mol %), CuCN (0.9 mg, 0.01 mmol, 5 mol %), *i*-PrOH (30.2 mg, 0.50 mmol, 2.5 equiv), and THF (1 mL, 0.2 M as final concentration). The reaction mixture was stirred for 18 h at room temperature. Hereafter, the solvent was evaporated by a gentle stream of N_2 and the residue was purified by flash chromatography (Eluent 2-5 % EtOAc/hexanes) on silica gel to afford the corresponding products **1** and **17**.

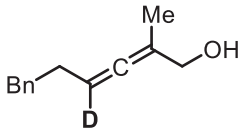
Labeling experiment:



S1, 0.20 mmol 0.24 mmol **42**, 66% yield (74% D)

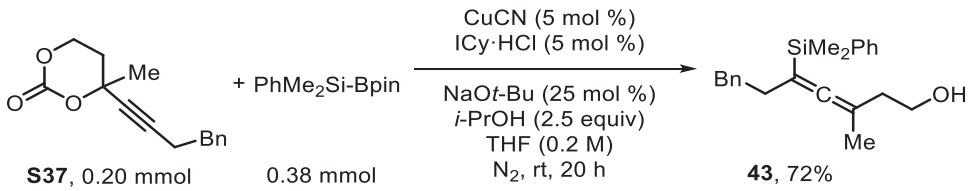
In a N_2-filled glove box, a dried 2 mL vial was charged with cyclic carbonate **S1** (46.1 mg, 0.20 mmol, 1.0 equiv), $B_2(neop)_2$ (55.9 mg, 0.24 mmol, 1.2 equiv), NaO*t*-Bu (5.0 mg, 0.05 mmol, 25 mol %), ICy·HCl (2.7 mg, 0.01 mmol, 5 mol %), CuCN (0.9 mg, 0.01 mmol, 5 mol %), and *i*-PrOD (137.0 mg, 2.00 mmol, 10 equiv). The reaction mixture was stirred for 16 h at room temperature. Hereafter, the solvent was evaporated by a gentle stream of N_2 and the residue was purified by flash chromatography on silica gel to afford the deuterated product **42**.

2-methyl-6-phenylhexa-2,3-dien-4-d-1-ol (**42**)



Colorless oil (25.0 mg, 66% yield, 74% D). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.33 – 7.27 (m, 2H), 7.23 – 7.16 (m, 3H), 5.33 – 5.27 (m, 0.26H), 3.87 (d, J = 1.4 Hz, 2H), 2.82 – 2.67 (m, 2H), 2.45 – 2.29 (m, 2H), 1.64 (s, 3H), 1.36 (s, 1H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 199.6, 141.6, 128.5, 128.3, 125.9, 101.1, 93.4, 63.8, 35.1, 30.3, 15.6.; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{13}H_{15}DNaO$ $[M + Na]^+$ 212.1156; Found 212.1153.

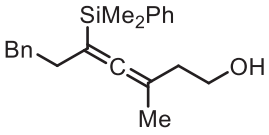
Procedure for the synthesis of silylated compound 43:



S37, 0.20 mmol 0.38 mmol **43**, 72%

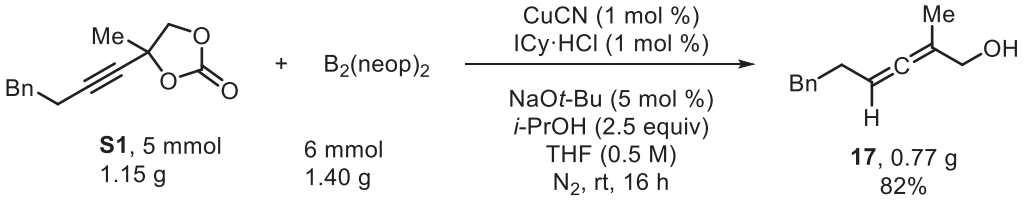
In a N_2-filled glove box, a dried 2 mL vial was charged with cyclic carbonate **S37** (48.9 mg, 0.20 mmol, 1.0 equiv), $PhMe_2Si$-Bpin (104.9 mg, 0.38 mmol, 1.9 equiv), NaO*t*-Bu (5.0 mg, 0.05 mmol, 25 mol %), ICy·HCl (2.7 mg, 0.01 mmol, 5 mol %), CuCN (0.9 mg, 0.01 mmol, 5 mol %), *i*-PrOH (30.2 mg, 0.50 mmol, 2.5 equiv) and THF(1 mL, 0.2 M as final concentration). The reaction mixture was stirred for 16 h at room temperature. Hereafter, the solvent was evaporated by a gentle stream of N_2 and the residue was purified by flash chromatography on silica gel to afford **43**.

5-(dimethyl(phenyl)silyl)-3-methyl-7-phenylhepta-3,4-dien-1-ol (**43**)



Colorless oil (48.5 mg, 72% yield). Eluent 2-5 % EtOAc/hexanes. **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.58 – 7.53 (m, 2H), 7.43 – 7.37 (m, 3H), 7.31 – 7.25 (m, 2H), 7.21 – 7.12 (m, 3H), 3.61 (t, *J* = 6.4 Hz, 2H), 2.77 – 2.70 (m, 2H), 2.33 – 2.25 (m, 2H), 2.20 – 2.12 (m, 2H), 1.66 (s, 3H), 1.43 (s, 1H), 0.40 (s, 3H), 0.40 (s, 3H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.4, 142.2, 138.2, 133.9, 129.2, 128.4, 128.2, 127.8, 125.7, 95.4, 91.8, 60.9, 36.9, 35.5, 31.5, 18.7, -2.8, -2.8.; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{22}H_{28}NaOSi$ $[M + Na]^+$ 359.1802; Found 359.1800.

Scale up experiment for 17:



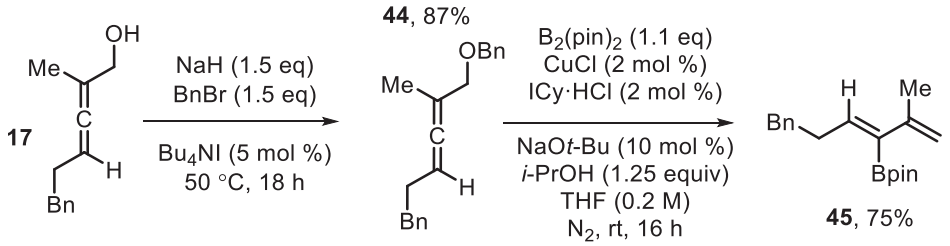
S1, 5 mmol
1.15 g

6 mmol
1.40 g

17, 0.77 g
82%

In a N_2-filled glove box, a dried 12 mL vial was charged with cyclic carbonate **S1** (1.15 g, 5 mmol, 1.0 equiv), $B_2(neop)_2$ (1.40 g, 6 mmol, 2.5 equiv), NaO*t*-Bu (0.12 g, 1.25 mmol, 5 mol %), ICy·HCl (13.4 mg, 0.05 mmol, 1 mol %), CuCN (4.5 mg, 0.05 mmol, 1 mol %), *i*-PrOH (0.76 g, 12.5 mmol, 2.5 equiv) and THF(10 mL). The reaction mixture was stirred for 16 h at room temperature. Hereafter, the solvent was evaporated by a gentle stream of N_2 and the residue was purified by flash chromatography (Eluent 2-5 % EtOAc/hexanes) on silica gel to afford the product **17** (0.77 g, 82%).

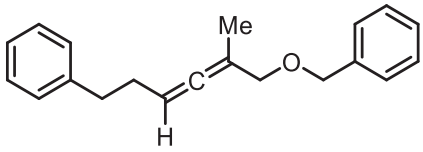
Procedure for the synthesis of compounds 44 and 45:



Step 1: A flask was charged with NaH (60% oil dispersion, 240 mg, 6.0 mmol) and THF (3.0 mL). To this mixture, a THF (3.0 mL) solution of **17** (753 mg, 4.0 mmol) was added dropwise at room temperature, and the resulting suspension was stirred for 15 minutes. Bu_4NI (73.8 mg, 0.2 mmol) and BnCl (1.03 g, 6.0 mmol) were added and the resulting mixture was stirred for 16 h at 50 ºC. The mixture was cooled to room temperature and H_2O and 1 N HCl aq. were added. Then, the mixture was extracted with Et_2O (3 × 20 mL) The organic layers were dried over $MgSO_4$. After filtration, all volatiles were removed in vacuo. The product was purified by silica gel column chromatography (Eluent 1-2 % Et_2O/hexanes).[16]

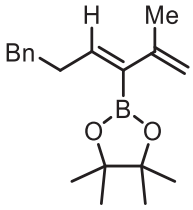
Step 2: In a N_2-filled glove box, a dried 2 mL vial was charged with **44** (55.6 mg, 0.2 mmol, 1.0 equiv), $B_2(pin)_2$ (56.4 mg, 0.22 mmol, 1.1 equiv), NaO*t*-Bu (2.0 mg, 0.02 mmol, 10 mol %), ICy·HCl (1.1 mg, 0.004 mmol, 2 mol %), CuCl (0.4 mg, 0.004 mmol, 2 mol %), *i*-PrOH (15.1 mg, 0.25 mmol, 1.25 equiv) and THF (1 mL, 0.2 M as final concentration). The reaction mixture was stirred for 16 h at room temperature. Hereafter, the solvent was evaporated by a gentle stream of N_2 and the residue was purified by flash chromatography (Eluent 1-3 % Et_2O/hexanes) on silica gel to afford the corresponding products.

(6-(benzyloxy)-5-methylhexa-3,4-dien-1-yl)benzene (**44**)



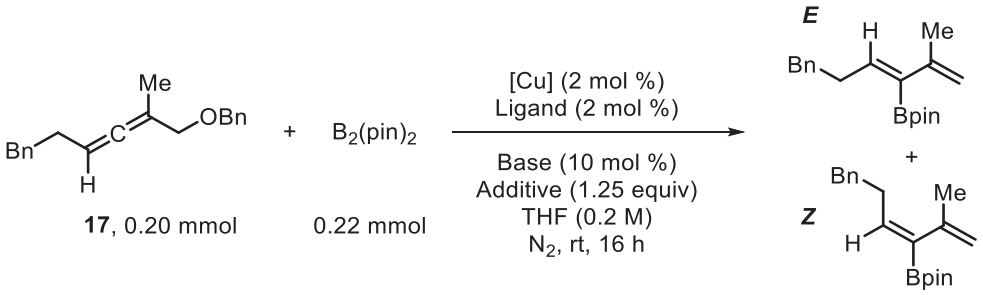
Step 1: Colorless oil (970 mg, 87% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.38 – 7.27 (m, 7H), 7.21 – 7.16 (m, 3H), 5.20 – 5.10 (m, 1H), 4.45 (d, *J* = 2.7 Hz, 2H), 3.93 (d, *J* = 2.0 Hz, 2H), 2.73 (t, *J* = 7.6 Hz, 2H), 2.40 – 2.29 (m, 3H), 1.69 (d, *J* = 2.9 Hz, 3H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 202.8, 141.7, 138.5, 128.5, 128.4, 128.3, 127.8, 127.5, 125.8, 96.9, 89.9, 72.4, 71.3, 35.5, 30.7, 16.1; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{20}H_{22}NaO$ $[M + Na]^+$ 301.1563; Found 301.1565.

(*E*)-4,4,5,5-tetramethyl-2-(2-methyl-6-phenylhexa-1,3-dien-3-yl)-1,3,2-dioxaborolane (**45**)



Step 2: Colorless oil (48.0 mg, 80% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.33 – 7.27 (m, 2H), 7.24 – 7.17 (m, 3H), 6.19 (t, *J* = 7.7 Hz, 1H), 5.01 (d, *J* = 1.9 Hz, 1H), 4.96 (t, *J* = 1.6 Hz, 1H), 2.80 – 2.72 (m, 2H), 2.63 – 2.52 (m, 2H), 1.92 – 1.86 (m, 3H), 1.34 (s, 12H); **^{13}C NMR** (101 MHz, $CDCl_3$) δ 145.1, 142.0, 140.7, 128.4, 128.3, 125.8, 114.2, 83.6, 36.4, 34.1, 25.0, 21.0. Carbon centers which are directly attached to the boron atoms were not observed, most likely due to quadrupolar relaxation; **HRMS** (ESI/TOF) *m/z* Calcd for $C_{19}H_{27}NaO_2{}^{11}B$ $[M + Na]^+$ 321.1996; Found 321.2007.

Screening of reaction conditions for the mono-borylation of 17:[a]



Entry	[Cu]	Ligand	Base	Additive	yield (%)[b]	*E/Z*
1[17]	CuCl	Xantphos	KO*t*-Bu	-	75	99:1
2	[(IPr)CuCl]	-	KO*t*-Bu	-	80	60:40
3	[(IPr)CuCl]	-	KO*t*-Bu	*i*-PrOH	89	91:9
4	CuCl	ICy·HCl	NaO*t*-Bu	*i*-PrOH	80	99:1
5	CuCN	ICy·HCl	NaO*t*-Bu	*i*-PrOH	trace	-

[a]Reaction conditions: **17** (0.2 mmol), $B_2(pin)_2$ (0.22 mmol), [Cu] (2 mol%), Ligand (2 mol %), Base (10 mol %), Additive (1.25 equiv), THF (1 mL), N_2, rt, 16 h. [b] Isolated yield.

UPLC-MS analysis for the reaction mixture leading to diborylated product 1:

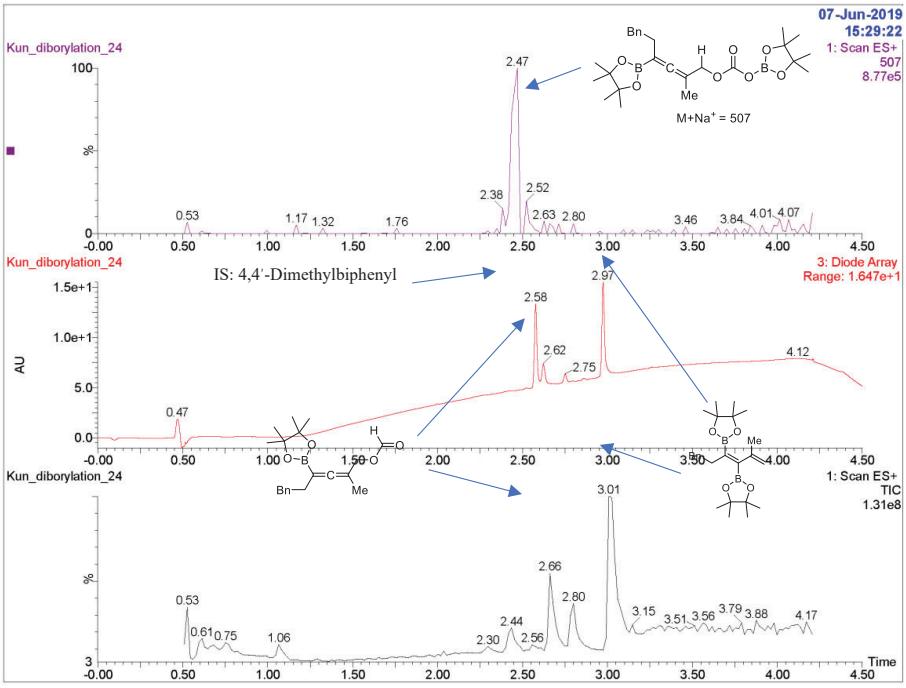


Figure S4.UPLC spectrum for the reaction mixture of **1**.

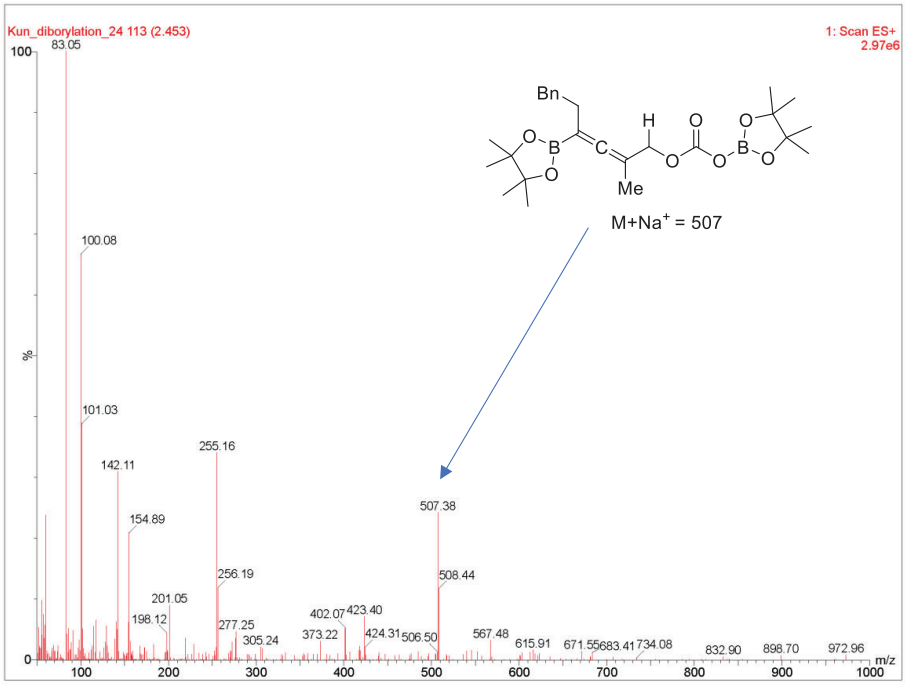


Figure S5. ESI+ spectrum for the presumed allyl-OCO_2Bpin intermediate.

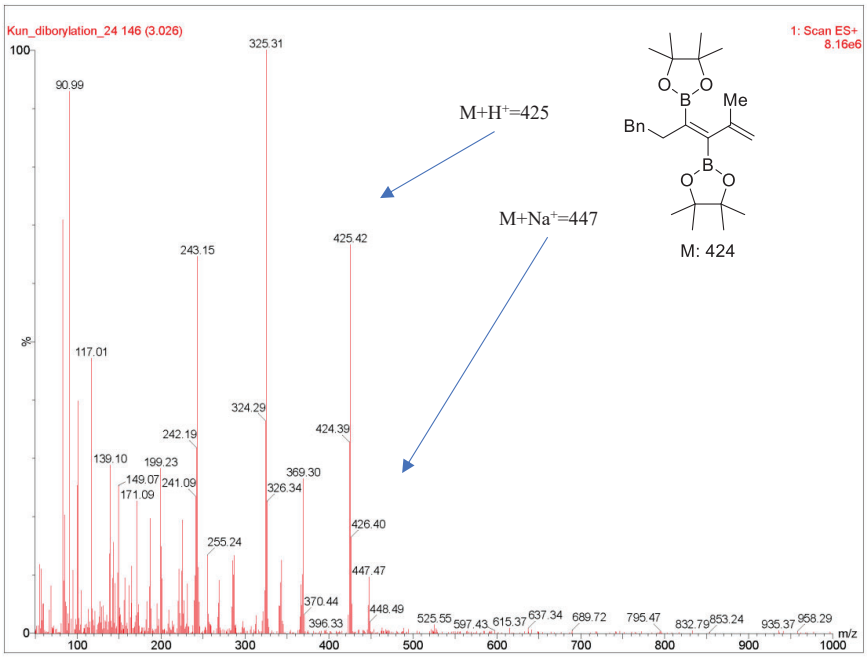


Figure S6. ESI+ spectrum for (*E*)-1,2-diborylated 1,3-diene **1**.

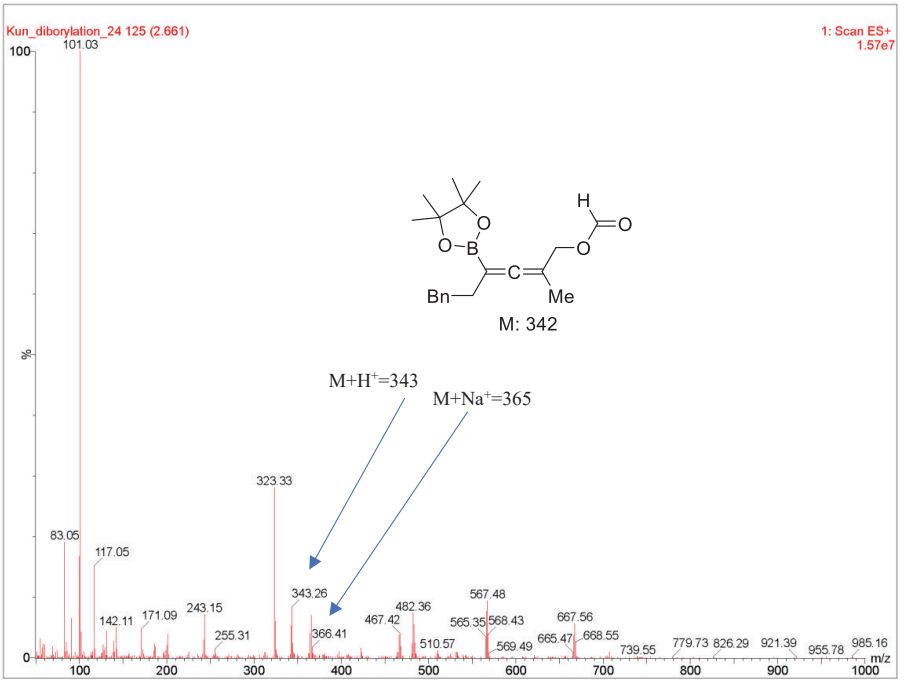
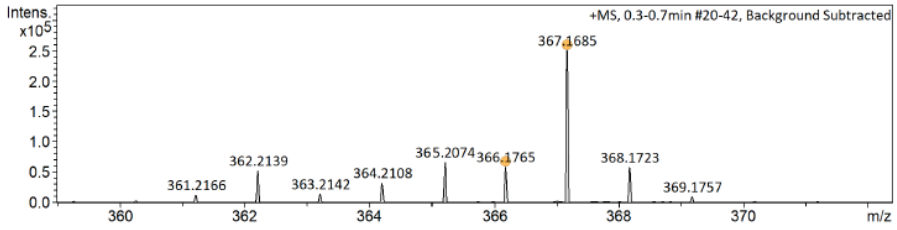


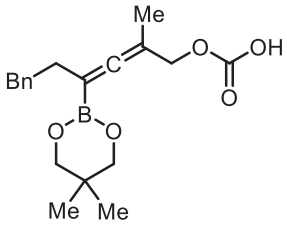
Figure S7. ESI+ spectrum for the precursor of **41**.

HRMS analysis for the reaction mixture of S1 with 2.5 equiv of $B_2(neop)_2$:

In a N_2-filled glove box, a dried 2 mL vial was charged with cyclic carbonate **S1** (46.1 mg, 0.20 mmol, 1.0 equiv), $B_2(neop)_2$ (116.5 mg, 0.50 mmol, 2.5 equiv), NaO*t*-Bu (5.0 mg, 0.05 mmol, 25 mol %), ICy·HCl (2.7 mg, 0.01 mmol, 5 mol %), CuCN (0.9 mg, 0.01 mmol, 5 mol %), *i*-PrOH (30.2 mg, 0.50 mmol, 2.5 equiv), and THF (1 mL; 0.2 M as final concentration). The reaction mixture was stirred for 18 h at room temperature. Hereafter, the reaction mixture was filtered by nylon syringe filter (pore size 0.22 μm, diam. 25 mm) and the filtrate was evaporated by a gentle stream of N_2. 2.1 mg of the mixture residue was submitted to the mass unit. The HRMS details are provided below.

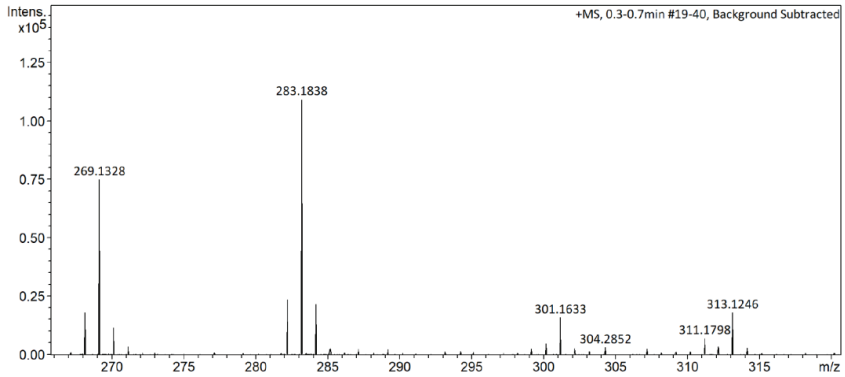


One of the possible components was assigned to the mono-borylated species as described below:



HRMS (ESI/TOF) *m/z* Calcd for $C_{19}H_{25}{}^{11}BO_5Na$ $[M + Na]^+$ 367.1687; Found 367.1685; Calcd for $C_{19}H_{25}{}^{10}BO_5Na$ $[M + Na]^+$ 366.1724; Found 366.1765; Calcd for $C_{19}H_{25}{}^{12}BO_5Na$ $[M + Na]^+$ 368.1721; Found 368.1723.

Two further (fragment) mono-cations were detected *m/z* = 269.1328 and 283.1838 that are likely *mono*-borylated species:



3.5.7 X-ray molecular structures for compounds 1 and 40a

The experimental procedure for collecting the X-ray data is the same as described in section 2.5.7.

Crystallographic details for 1: $C_{25}H_{38}B_2O_4$, *Mr* = 424.17, orthorhombic, Pbca, *a* = 13.1922(3) Å, *b* = 11.6097(3) Å, *c* = 32.6411(8) Å, *V* = 4999.2(2) Å^3, *Z* = 8, ρ_{calc} = 1.127 g/cm^3, μ = 0.073 mm^{-1}, λ = 0.71073, *T* = 293(2) K, *F*(000) = 1840, crystal size = 0.5 × 0.5 × 0.4 mm^3, 2θ(min) = 4.838, 2θ(max) = 64.262, 50473 reflections measured, 8335 unique (R_{int} = 0.0328), GoF = 1.029, R_1 = 0.0508 and wR_2 = 0.1345 [I>2σ(I)], R_1 = 0.0625 and wR_2 = 0.1406 (all indices), min/max residual density = -0.21/0.53 [e·Å^{-3}]. CCDC number 2035474.

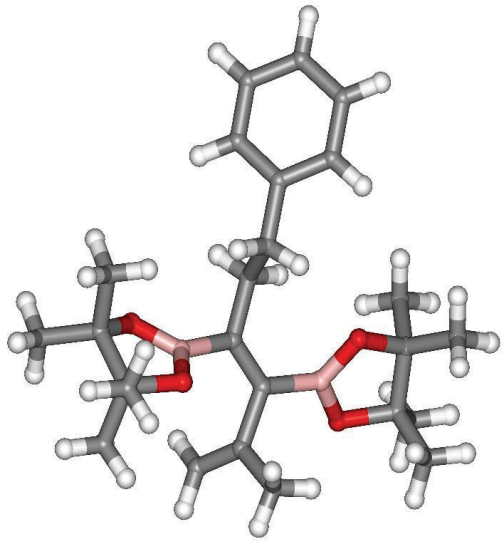


Figure S8. X-ray molecular structure of **1**.

Crystallographic details for 40a: $C_{21}H_{31}BO_5Si$, $Mr = 402.36$, triclinic, P-1, $a = 10.9287(3)$ Å, $b = 11.2224(3)$ Å, $c = 11.6217(4)$ Å, $\alpha = 95.434(2)°$, $\beta = 112.102(3)°$, $\gamma = 116.422(3)°$, $V = 1122.10(7)$ Å^3, $Z = 2$, $\rho_{calc} = 1.191$ g/cm^3, $\mu = 0.132$ mm^{-1}, $\lambda = 0.71073$, $T = 293(2)$ K, $F(000) = 432$, crystal size = 0.13 × 0.11 × 0.10 mm^3, $2\theta(\text{min}) = 4.414°$, $2\theta(\text{max}) = 64.298°$, 21246 reflections measured, 7363 unique ($R_{int} = 0.0446$), GoF = 1.059, $R_1 = 0.0468$ and $wR_2 = 0.1299$ [$I>2\sigma(I)$], $R_1 = 0.0560$ and w$R_2 = 0.1351$ (all indices), min/max residual density = -0.53/0.62 [e·Å^{-3}]. CCDC number 2035473.

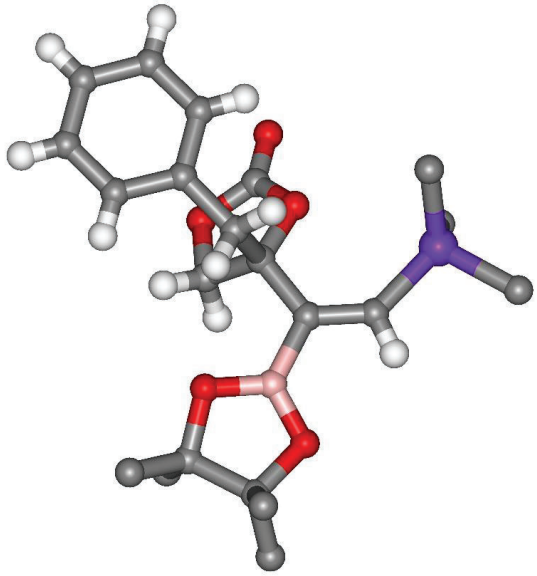


Figure S9. X-ray molecular structure of **40a**.

3.6 References

1. (a) Burns, M.; Essafi, S.; Bame, J. R.; Bull, S. P.; Webster, M. P.; Balieu, S.; Dale, J. W.; Butts, C. P.; Harvey, J. N.; Aggarwal, V. K. *Nature* **2014***, 513*, 183; (b) Diner, C.; Szabó, K. J. *J. Am. Chem. Soc.* **2017**, *139*, 2; (c) Balieu, S.; Hallett; G. E.; Burns, M.; Bootwicha, T.; Studley, J.; Aggarwal, V. K. *J. Am. Chem. Soc.* **2017**, *137*, 4398; (d) Meng, F.; McGrath, K. P.; Hoveyda, A. H. *Nature* **2014**, *513*, 367; (e) Zhang, S.; Pozo, J.; Romiti, F.; Mu, Y.; Torker, S.; Hoveyda, A. H. *Science* **2019**, *364*, 45; (f) Takahashi, F.; Nogi, K.; Sasamori, T.; Yorimitsu, H.; *Org. Lett.* **2019**, *21*, 4739; (g) Fyfe, J. W. B.; Watson, A. J. B.; *Chem* **2017**, *3*, 31.

2. (a) Miyaura, N.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457; (b) Suginome, M. and Ohmura, T. in: Boronic Acids: Preparation and Applications in Organic Synthesis, Medicine and Materials, 2nd ed., D. G. Hall (ed.), Wiley-VCH, Weinheim, **2011**, p. 171-212; (c) Ishiyama, T.; Miyaura, N. *Chem. Rec.* **2004**, *3*, 271; (d) Carreras, J.; Caballero, A.; Pérez, P. J.; *Chem. Asian J.* **2019**, *14*, 329; (e) Yoshida, H. *ACS Catal* **2016**, *6*, 1799. (f) Takaya, J.; Iwasawa, N. *ACS Catal.* **2012**, *2*, 1993; (g) Marder, T. B.; Norman, N. C. *Top. Catal.* **1998**, *5*, 63; (h) Yoshida, H. *ACS Catal.* **2016**, *6*, 1799; (i) Neeve, E. C.; Geier, S. J.; I. Mkhalid, I. A.; Westcoot, S. A.; Marder, T. B. *Chem. Rev.* **2016**, *116*, 9091; (j) Semba, K.; Fujihara, T.; Terao, J.; Tsuji, Y. *Tetrahedron* **2015**, *71*, 2183. For some original (recent) contributions: (k) Miralles, N.; Alam, R.; Szabó, K. J.; Fernández, E. *Angew. Chem. Int. Ed.* **2016**, *55*, 4303; (l) Trost, B.; Zhang, G. *J. Am. Chem. Soc.* **2020**, *142*, 7312; (m) Miura, T.; Nakahashi, J.; Sasatsu, T.; Murakami, M. *Angew. Chem. Int. Ed.* **2019**, *58*, 1138; (n) Hu, Y.; Sun, W.; Zhang, T.; Xu, N.; Xu, J.; Lan, Y.; Liu, C. *Angew. Chem. Int. Ed.* **2019**, *58*, 15813.

3. Ito, H.; Sasaki, Y.; Sawamura, M. *J. Am. Chem. Soc.* **2008**, *130*, 15774.

4. (a) Jarava-Barrera, C.; Parra, A.; Amenjs, L.; Arroyo, A.; Tortosa, M. *Chem. Eur. J.* **2017**, *23*, 17478. For related chemistry involving allylic precursors: (b) Amenós,

L.; Trulli, L.; Nóvoa, L.; Parra, A.; Tortosa, M. *Angew. Chem. Int. Ed.* **2019**, *58*, 3188; (c) Amenós, L.; Nóvoa, L.; Trulli, L.; Arroyo-Bondía, A.; Parra, A.; Tortosa, M. *ACS Catal.* **2019**, *9*, 6583.

5. Deutsch, C.; Lipshutz, B. H.; Krause, N. *Angew. Chem. Int. Ed.* **2007**, *46*, 1650.

6. Zhong, C.; Sasaki, Y.; Ito, H.; Sawamura, M.; *Chem. Commun.* **2009**, 5850.

7. For selected recent examples: (a) Liu, K.; Khan, I.; Cheng, J.; Hsueh, Y. J.; Zhang, Y. J. *ACS Catal.* **2018**, *8*, 11600; (b) Cai, A.; Guo, W.; Martínez-Rodríguez, L.; Kleij, A. W. *J. Am. Chem. Soc.* **2016**, *138*, 14194; (c) Zhao, C.; Shah, B. H.; Khan, I.; Kan, Y.; Zhang, Y. J. *Org. Lett.* **2019**, *21*, 9045; (d) Guo, W.; Martínez-Rodríguez, L.; Kuniyil, R.; Martin, E.; Escudero-Adán, E. C.; Maseras, F.; Kleij, A. W. *J. Am. Chem. Soc.* **2016**, *138*, 11970; (e) Miralles, N.; Gómez, J. E.; Kleij, A. W.; Fernández, E. *Org. Lett.* **2017**, *19*, 6096; (f) Guo, W.; Kuniyil, R.; Gómez, J. E.; Maseras, F.; Kleij, A. W. *J. Am. Chem. Soc.* **2018**, *140*, 3981; For reviews: (g) Guo, W.; Gómez, J. E.; Cristòfol, À.; Xie, J.; Kleij, A. W. *Angew. Chem. Int. Ed.* **2018**, *57*, 13735; (h) Gava, R.; Fernández, E. *Org. Biomol. Chem.* **2019**, *17*, 6317.

8. (a) Gómez, J. E.; Cristofol, A.; Kleij, A. W. *Angew. Chem. Int. Ed.* **2019**, *58* , 3903; (b) Tian, L.; Gong, L.; Zhang,X. *Adv. Synth. Catal.* **2018**, *360*, 2055; (c) Tang, X.; Woodward, S.; Krause, N. Eur. *J. Org. Chem.* **2009**, 2836; (d) Zhang, Y.-C.; Zhang, B.-W.; Geng, R.-L.; Song, J. *Org. Lett.* **2018**, *20*, 7907; (e) Zhang, Z.-J.; Zhang, L.; Geng, R.-L.; Song, J.; Chen, X.-H.; Gong, L.-Z. *Angew. Chem. Int. Ed.* **2019**, *58*, 12190; for the conversion of allylic lactone surrogates: (f) Gómez, J. E.; Guo, W.; Gaspa, S.; Kleij, A. W. *Angew. Chem. Int. Ed.* **2017**, *56*, 15035.

9. Guo, K.; Kleij, A. W. *Org. Lett.* **2020**, *22*, 3942.

10. (a) Krause, N.; Winter, C. *Chem. Rev.* **2011**, *111*, 1994; (b) Kessler, S. N.; Hundemer, F.; Bäckvall, J.-E. *ACS Catal.* **2016**, *6*, 7448; c) Ye, J.; Fan, W.; Ma, S. *Chem. Eur. J.* **2013**, *19*, 716; (d) Jiang,Y.; Diagne, A. B.; Thomson, R. J.;

Schaus, S. E. *J. Am. Chem. Soc.* **2017**, *139*, 1998; (e) Morita, N.; Krause, N. *Org. Lett.* **2004**, *6*, 4121; (f) Li, S.; Miao, B.; Yuan, W.; Ma, S. *Org. Lett.* **2013**, *15*, 977; For related *α*-thioallenes: (g) Morita, N.; Krause, N. *Angew. Chem. Int. Ed.* **2006**, *45*, 1897.

11. Some of these diborylated products were reported before by Szabó and coworkers using either a dual catalytic (Pd, Cu) or Cu-mediated (CuCl/PCy3) protocol, see: (a) Zhao, T. S. N.; Yang, Y.; Lessing, T.; Szabó, K. J. *J. Am. Chem. Soc.* **2014**, *136*, 7563. The isolated products had, however, substantially lower E/Z ratios even in the presence of 50 mol % CuCl as previously reported (cf., 1-12) and thus our results show the importance of both the nature of the supporting ligand and propargylic surrogate in this diborylation manifold. See also: (b) Zhao, T. S. N.; Zhao, J.; Szabó, K. J. *Org. Lett.* **2015**, *17*, 2290. See also ref. 3.

12. For more details see CCDC-2035473 and 2035474.

13. (a) Pietsch, S.; Paul, U. I.; Cade, A.; Ingleson, M. J.; Radius, U.; Marder,T. B. *Chem. Eur. J.* **2015**, *21*, 9018; (b) Liu, M.-Y.; Hong, S.-B.; Zhang, W.; Deng, W. *Chin. Chem. Lett.* **2015**, *26*, 373; (c) Joshi-Pangu, A.; Ma, X.; Diane, M.; Iqbal, S.; Kribs, R. J.; Huang, R.; Wang, C.-Y.; Biscoe, M. R. *J. Org. Chem.* **2012**, *77*, 15, 6629; (d) Hu, J.; Zhao, Y.; Liu, J.; Zhang, Y.; Shi, Z. *Angew. Chem. Int. Ed.* **2016**, *55*, 8718; (e) Guo, L.; Rueping, M. *Chem. Eur. J.* **2016**, *22*, 16787.

14. Martin and coworkers reported a Ni-catalyzed dichotomic *ipso*-borylation of aryl methyl ethers providing borylated products as a result of either C(sp^3) or C(sp^2) borylation, see: Zarate, C.; Manzano, R.; Martin, R. *J. Am. Chem. Soc.* **2015**, *137*, 6754.

15. (a) Chae, Y. M.; Bae, J. S.; Moon, J. H.; Lee, J. Y.; Yun, J. *Adv. Synth. Catal.* **2014**, *356*, 843; b) Kim, Y. E.; Li, D.; Yun, J. *Dalton Trans.* **2015**, *44*, 12091.

16. For the synthesis of mono-borylated allenes such as **41** see: Zhao, J.; Szabó, K. J. *Angew. Chem. Int. Ed.* **2016**, *55*, 1502. See also reference 3.

17. Semba, K.; Fujihara, T.; Terao, J.; Tsuji, Y. *Angew. Chem. Int. Ed.* **2013**, *52*, 12400.

18. For the potential of oxygen donor ligands to bridge between alkyl boronates and a Cu carbene: Li, Z.; Zhang, L.; Nishiura, M.; Luo, G.; Luo, Y.; Hou, Z. *J. Am. Chem. Soc.* **2020**, *142*, 1966.

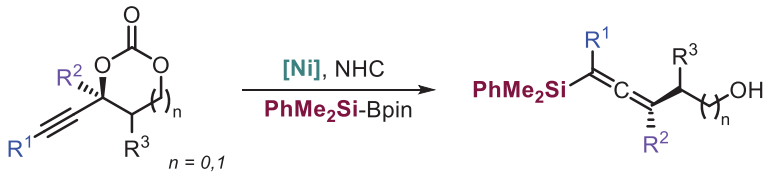
19. Transmetalation involving Cu-carbene complexes and aryl- and alkyl-boronates is well-documented, see: (a) Ohishi, T.; Nishiura, M.; Hou, Z. *Angew. Chem. Int. Ed.* **2008**, *47*, 5792; (b) Ohishi, T.; Zhang, L.; Nishiura, M.; Hou, Z. *Angew. Chem. Int. Ed.* **2011**, *50*, 8114; (c) Shintani, R.; Takatsu, K.; Hayashi, T. *Chem. Commun.* **2010**, *46*, 6822.

20. Li, J.; Kong, W.; Fu, C.; Ma, S. *J. Org. Chem.* **2009**, *74*, 5104-5106.

21. Suzuki, A.; Miyaura, N.; Itoh, M.; Brown, H. C.; Jacob, P. III *Synthesis* **1973**, *305*.

Chapter 4

Ni-Catalyzed Decarboxylative Silylation of Alkynyl Carbonates: Access to Chiral Allenes via Enantiospecific Conversions



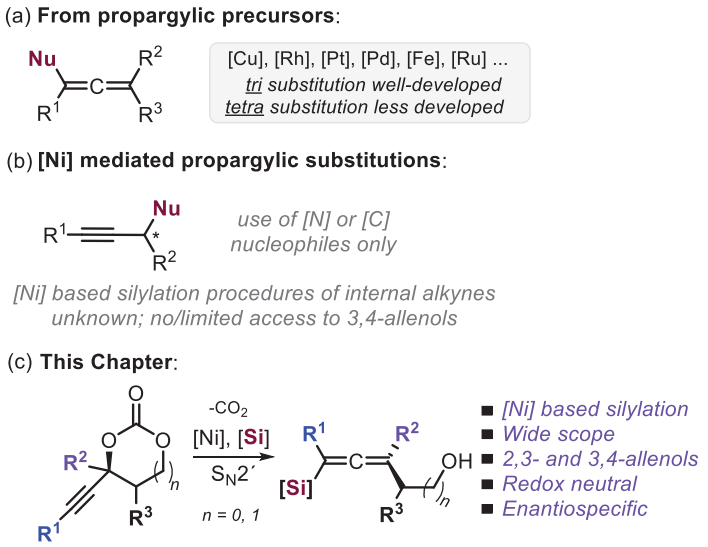
- This chapter is currently prepared for submission -

4.1 Introduction

Propargylic substitution reactions are among the most important transformations in organic synthesis allowing the efficient and reliable synthesis of new carbon-carbon and carbon-heteroatom bonds.[1] These conversions are typically promoted by transition metal catalysts and have been extended from simple propargylic alcohols featuring terminal alkyne groups to substrates comprising internal alkynes leading to useful synthons such as allenes (Scheme 1a, Nu = nucleophile). Further seminal advances in the area have led to a plethora of attractive asymmetric variants of propargylic substitutions[2] affording chiral synthons with a diversity of functionalities, expanding their scope and application in natural product synthesis.[3]

It is generally accepted that a metal(allenylidene) species plays a key role in the mechanistic scenario when a propargylic substrate containing a terminal alkyne is converted.[1e,4] Such a manifold is obviously not feasible for propargylic precursors that have internal triple bonds, and their metal-catalyzed activation and conversion is suggested to involve a propargylic carbocation[5] by a formal S_N2 displacement of the leaving group. Despite being distinct, for the latter category of propargylic substitutions several enantioselective protocols have evolved over the last decade.[6] Of our particular interest is the demonstration of Ni-catalysis to forge chiral propargylic synthons with internal alkyne groups.[2c-d,7] We recently reported the use of new propargylic surrogates based on alkyne-functionalized cyclic carbonates that under appropriate Cu-catalysis can be converted into silylated[8] and borylated allenes.[9] In both cases, there is a key β-O-elimination step that empowers the propargylic substitution process. However, carbometalation followed by β-O-elimination is unprecedented with Ni,[10] while Ni-promoted propargylic silylation to our knowledge remains unknown[11] despite the report of several successful Ni-catalyzed propargylic substitution processes using amine and carbon pronucleophiles (Scheme 1b).[2c –d,5,7]

4.2 Project Aims and Strategy

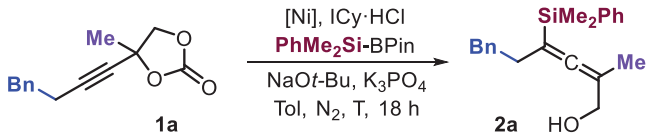


Scheme 1. Previous work and limitations in Ni-catalyzed propargylic substitutions, and current focus in this chapter.

Encouraged by this apparent lack of scope in nucleophilic reaction partners described in section 4.1, we set out to develop a Ni-based procedure for the silylation of alkynyl cyclic carbonates with the aim to induce a selective S_N2' silylation affording the target allenols (Scheme 1c). These allenols are important building blocks in synthetic chemistry,[12] while the catalytic formation of silylated allenes using other metals (though dominated by Cu) has been an active field of research.[13] We envisaged that a successful Ni-catalyzed silylation protocol could also be useful in the context of the preparation of chiral silyl-allenes via enantiospecific, point-to-axial chirality transfer reactions[13a+e,14] involving appropriate chiral alkyne carbonate precursors. These and similar transformations build on the known and more general potential of Ni catalysts in enantio-retentive cross-coupling events,[15] and create further value for new Ni-based propargylic substitution protocols.

4.3 Results and discussion

Table 1. Screening data towards the synthesis of silylated 2,3-allenol **2a** from **1a**.[a]

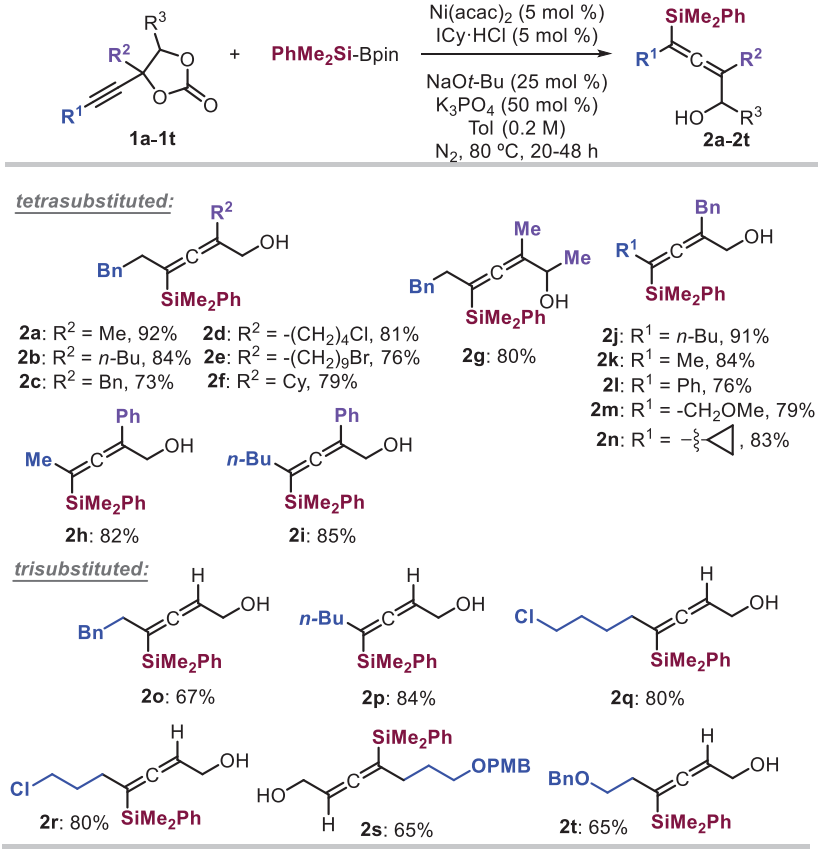


Entry	[TM]	Ligand	Base	Additive	Solvent	T (ºC)	Yield (%)[b]
1	$Pd(PPh_3)_4$	ICy·HCl	NaO*t*-Bu	*i*-PrOH	THF	rt	0
2	$Pd(PPh_3)_4$	CuCl	NaO*t*-Bu	*i*-PrOH	THF	rt	–
3	$Ni(cod)_2$	ICy·HCl	NaO*t*-Bu	*i*-PrOH	THF	rt	0
4	$Ni(cod)_2$	ICy·HCl	NaO*t*-Bu	K_3PO_4	THF	rt	0
5	$Ni(cod)_2$	ICy·HCl	NaO*t*-Bu	K_3PO_4	Tol	rt	36
6	$Ni(cod)_2$	ICy·HCl	NaO*t*-Bu	K_3PO_4, *i*-PrOH	Tol	rt	70
7	$Ni(cod)_2$	ICy·HCl	NaO*t*-Bu	K_3PO_4	Tol	80	70
8	$Ni(cod)_2$	–	NaO*t*-Bu	K_3PO_4	Tol	80	0
9	$Ni(cod)_2$	ICy·HCl	–	K_3PO_4	Tol	80	68
10	$Ni(acac)_2$	ICy·HCl	NaO*t*-Bu	K_3PO_4	Tol	80	82
11	$Ni(acac)_2$	ICy·HCl	–	K_3PO_4	Tol	80	81
12[c]	$Ni(acac)_2$	ICy·HCl	NaO*t*-Bu	–	Tol	80	0
13[d]	$Ni(acac)_2$	ICy·HCl	NaO*t*-Bu	K_3PO_4	Tol	80	44
14[e]	$Ni(acac)_2$	ICy·HCl	NaO*t*-Bu	K_3PO_4	Tol	rt	64
15[f]	$Ni(acac)_2$	ICy·HCl	NaO*t*-Bu	K_3PO_4	Tol	80	67
16[g]	$Ni(acac)_2$	ICy·HCl	NaO*t*-Bu	K_3PO_4	Tol	80	85
17[h]	$Ni(acac)_2$	ICy·HCl	NaO*t*-Bu	K_3PO_4	Tol	80	81
18[i]	$Ni(acac)_2$	ICy·HCl	NaO*t*-Bu	K_3PO_4	Tol	80	85
19[j]	$Ni(acac)_2$	ICy·HCl	–	K_3PO_4	Tol	80	64
20[j]	$Ni(acac)_2$	ICy·HCl	NaO*t*-Bu	K_3PO_4	Tol	80	77
21[g, i]	$Ni(acac)_2$	ICy·HCl	NaO*t*-Bu	K_3PO_4	Tol	80	72
22[g, i]	$Ni(acac)_2$	ICy·HCl	–	K_3PO_4	Tol	80	74
23	$Ni(OAc)_2{\cdot}4H_2O$	ICy·HCl	NaO*t*-Bu	K_3PO_4	Tol	80	78
24[g, i]	$Ni(OAc)_2{\cdot}4H_2O$	ICy·HCl	NaO*t*-Bu	K_3PO_4	Tol	80	23
25[g, i]	$Ni(OAc)_2{\cdot}4H_2O$	ICy·HCl	–	K_3PO_4	Tol	80	66
26[g, i, j]	$Ni(OAc)_2{\cdot}4H_2O$	ICy·HCl	–	K_3PO_4	Tol	80	56
27[i]	$Ni(OAc)_2{\cdot}4H_2O$	ICy·HCl	–	K_3PO_4	Tol	80	38
28	$NiCl_2{\cdot}6H_2O$	ICy·HCl	NaO*t*-Bu	K_3PO_4	Tol	80	76
29	$NiBr_2{\cdot}3H_2O$	ICy·HCl	NaO*t*-Bu	K_3PO_4	Tol	80	80
30	NiI_2	ICy·HCl	NaO*t*-Bu	K_3PO_4	Tol	80	64
31	$NiBr_2$	ICy·HCl	NaO*t*-Bu	K_3PO_4	Tol	80	82
32	$NiBr_2{\cdot}$glyme	ICy·HCl	NaO*t*-Bu	K_3PO_4	Tol	80	80
33	$Ni(dppp)Cl_2$	ICy·HCl	NaO*t*-Bu	K_3PO_4	Tol	80	26

Table 1 - *Continued*

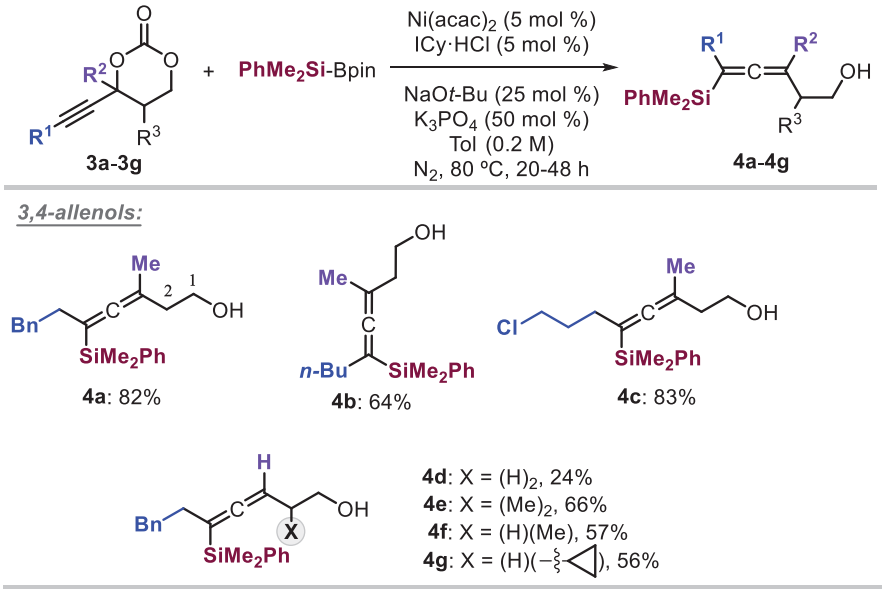
Entry	[TM]	Ligand	Base	Additive	Solvent	T (ºC)	Yield (%)[b]
34	$Ni(dppp)Cl_2$	–	NaO*t*-Bu	K_3PO_4	Tol	80	8
35	–	ICy·HCl	NaO*t*-Bu	K_3PO_4	Tol	80	0
36	$Ni(acac)_2$	DPPP	NaO*t*-Bu	K_3PO_4	Tol	80	0
37[i, l]	$Ni(acac)_2$	ICy·HCl	NaO*t*-Bu	K_3PO_4	Tol	80	92

[a]Reaction condition: alkynyl carbonate substrate (0.20 mmol), $PhMe_2Si$-Bpin (0.24 mmol), [TM] (5 mol %), ligand (5 mol %), base (25 mol %), additive (2.5 equiv), solvent (1 mL), N_2, temperature indicated, 18 h. [b]Isolated yield. [c]NaO*t*-Bu (2.5 equiv). [d][TM] (2 mol %), ligand (2 mol %). [e]R.t. [f]$PhMe_2Si$-Bpin (0.21 mmol). [g][TM] (2 mol %). [h]Additive (1.2 equiv). [i]Additive (50 mol %). [j]Air. [l]$PhMe_2Si$-Bpin (0.30 mmol).

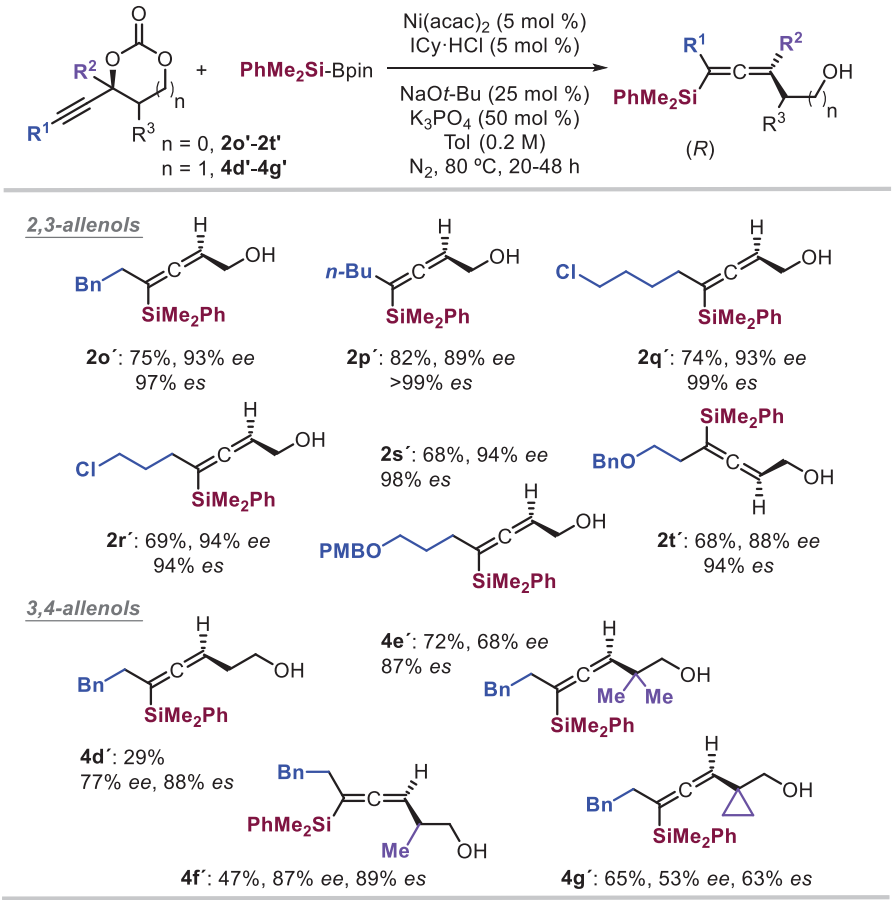


Scheme 2. Preparation of 2,3-allenols via the Ni-mediated silylation of alkynyl cyclic carbonates.

We started to screen reactions conditions that involved various Ni precursors, solvent and additives while varying the reaction temperature (Table 1) and using $PhMe_2Si$-BPin as silylating agent.[16] The use of $Ni(cod)_2$ as a precursor combined with an *N*-heterocyclic carbene (ICy·HCl = 1,3-dicyclohexylimidazolium chloride) in the presence of NaO*t*-Bu and K_3PO_4 as base additives provided the desired product **2a** in up to 70% yield at 80 ºC (Table 1, entries 3-9). The presence of the carbene ligand was essential (entry 8), whereas the reaction performed in the absence of NaO*t*-Bu was slightly less productive (entry 9). We then were pleased to find that $Ni(cod)_2$ could be replaced by $Ni(acac)_2$ enabling a more practical approach towards **2a** (entries 10-22). Several experiments demonstrated that the presence of the [Ni] precursor (entry 35) and K_3PO_4 (entry 12) are necessary, and that the reactions may be performed in air without significantly affecting the product yield (entry 20). The best yield for **2a** (92%) was then attained by slightly increasing the relative amount of the silyl-substrate (entry 37). Other Ni precursors were also productive in this protocol, but further studies were carried out using $Ni(acac)_2$.



Scheme 3. Preparation of 3,4-allenols via the Ni-mediated silylation of alkynyl cyclic carbonates.

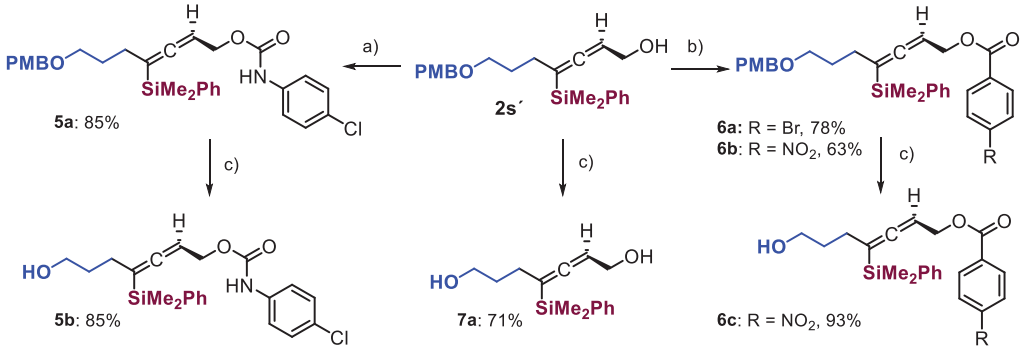


Scheme 4. Enantiospecific transformations of alkynyl cyclic carbonates giving axially chiral 2,3- and 3,4-allenols.

The scope of products was then studied by variation of the substituents of the alkyne cyclic carbonates **1** (Scheme 2). The versatility of these carbonate precursors not only allows for modulation of the steric and electronic parameters of the allenol products but also provides a simple approach to expand the products from 2,3-allenols using five-membered carbonates to 3,4-allenols via six-membered carbonates. A rather wide range of tetra-substituted (**2a-2n**) and trisubstituted 2,3-allenols (**2o-2t**) could be prepared using the optimized reaction conditions with isolated product yields typically in the range of 70–90%.

The protocol is compatible with the introduction of various (functional) groups such as alkyl halides (**2d**, **2e**, **2q** and **2r**), protected alcohols (**2s** and **2t**) and different cycloalkyls (**2f** and **2n**).

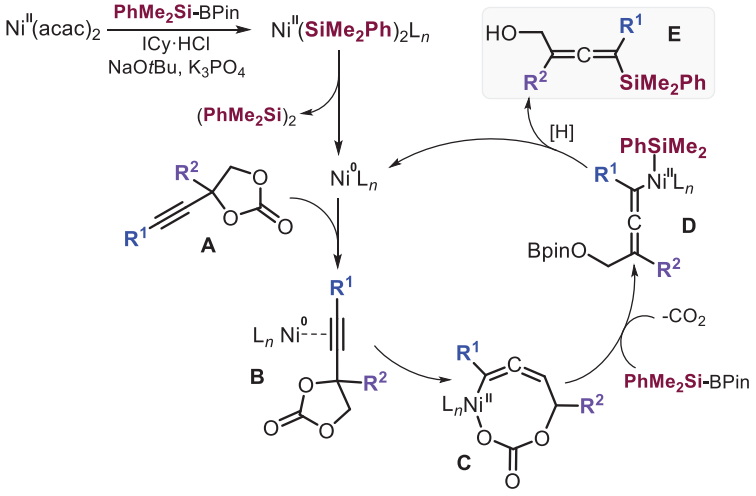
More importantly, the product scope is easily extended to 3,4-allenols (**4a**-**4g**) which can be isolated in appreciable yields (Scheme 3). This exemplifies the versatile nature of alkynyl cyclic carbonates of type **1** and **3** versus the use of other known propargylic precursors. Another asset of using these alkyne carbonates is their propensity to extend the substrate scope to chiral precursors providing impetus for Ni-mediated point-to-axial chirality transfer (Scheme 4), and subsequently an easy entry for the preparation of enantio-enriched silylated 2,3- (**2o´** to **2t´**) and 3,4-allenols (**4d´**to **4g´**). In most investigated cases the developed Ni-catalyzed protocol showed high levels of enantio-specificity except for **4g´** (63% *es*), which may the result of the highly rigid nature of the cyclopropyl substitution. To demonstrate the robustness of these allenols, **2s´** (94% *ee*) was subjected to different sequences of carbamation/deprotection or esterification/deprotection (Scheme 5) giving thereby access to a wider set of potentially useful building blocks in good yields.



a). silyl allenol (1.0 equiv), isocyanate (1.2 equiv), Et_3N (2.0 equiv), DCM (0.3 M),rt, 12 h
b). silyl allenol (1.0 equiv), acid chloride (1.5 equiv), DMAP(10 mol %), Et_3N (3.0 equiv), DCM (0.2 M), 0°C - rt, 12 h
c).PMB protected alcohols (1.0 equiv), DDQ (1.5 equiv), DCM (0.2 M), phosphate buffer (0.1 M), rt, 2 h

Scheme 5. Several post-modifications carried out for compound **2s´**. See for conditions a-c the Experimental Section.

The configuration of the chiral allenol **2s'** (*all allenols are liquids*) was investigated by CD spectroscopy and compared to the computationally determined configurations of both (*R*) and (*S*).[14e] From these studies, it could be concluded that the formation of the (*R*)-configured 2,3-allenol product is favored (details are provided in the Experimental Section). The configurations of the other chiral allenols were assigned by analogy. In the case of five-membered cyclic carbonates, a formal retention of the chiral configuration (cf., (*R*)-**3g´**) was therefore observed.



Scheme 6. Envisioned manifold for the Ni-catalyzed 2,3-allenol formation from alkynyl cyclic carbonates.

A simplified mechanistic proposal is summarized in Scheme 6 for the synthesis of 2,3-allenols. First, the Ni(II) precursor is reduced to Ni(0) in the presence of the silyl-borane reagent.[17] The fact that both Ni(II) and Ni(0) precursors lead to productive catalysis suggests that the presence of low-valent Ni is requisite to start the catalytic cycle. The first step is the activation of the alkynyl carbonate **A** through the intermediacy of a π-complex **B** following oxidative addition giving a *C,O*-chelated nickelacycle **C**. The latter, according to the final product, should evolve into a silyl-Ni(allenyl) species **D** after decarboxylation of **C** occurs, furnishing the 2,3-allenol **E** and setting up the system for additional turnover.

4.4 Conclusion

In summary, in this chapter we present a new Ni-mediated synthesis of a wide scope of 2,3- and 3,4-allenols, including chiral synthons produced via an enantiospecific variant. This protocol further expands the portfolio of functional allene building blocks for advanced synthetic programs.

4.5 Experimental Section

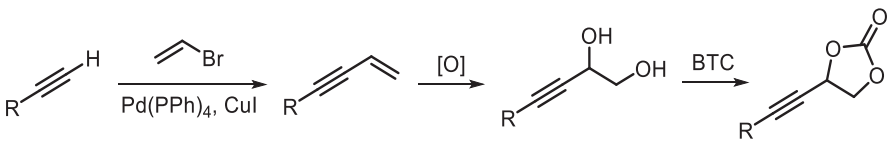
4.5.1 General information

Please refer to section **2.5.1** for the specific information.

4.5.2 Synthesis of the starting materials

Cyclic carbonates (**1a**-**1n**) were prepared according to the procedures reported in the literature.[8]

General procedure A for the synthesis of *racemic* 5-membered cyclic carbonates:



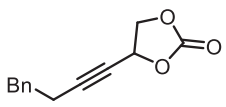
Step 1: Under an argon atmosphere, $Pd(PPh_3)_4$ (57.8 mg, 0.5 mol %) and CuI (38.1 mg, 2 mol %) were added into an oven-dried Schlenk flask, followed by addition of dry degassed diethylamine (0.50 mL/1.0 mmol alkyne), and the mixture was then cooled by an ice bath. The corresponding terminal alkyne (10.0 mmol, 1.0 equiv) and vinyl bromide (6.5 mmol, 1.3 equiv, 1.0 M in THF) was added dropwise via a syringe. The resulting mixture was left to stir and warmed up to room temperature until complete conversion of the starting material was observed by TLC. The reaction mixture was washed with water followed by extraction with *n*-pentane/diethyl ether (1:1). The combined organic layers were washed with 1 M HCl and dried over anhydrous Na_2SO_4. After concentration under vacuum, the residue was purified by column chromatography over silica gel using hexanes as eluent.[18]

Step 2: The enyne (1.0 equiv) and $K_3Fe(CN)_6$ (3.0 equiv), K_2CO_3 (3.0 equiv), quinuclidine (15 mol %), $K_2OsO_2(OH)_4$ (5 mol %) and methane sulfonamide (1.0 equiv) were suspended in *t*-BuOH/H_2O (50 mL each) and the mixture was stirred at r.t. for 48 h. Na_2SO_3 (15 g) was added, the mixture was extracted with EtOAc, the combined organic

layers were dried over Na_2SO_4 and concentrated under reduced pressure. The crude was purified by flash column chromatography over silica gel (hexanes/ethyl acetate, 1:1) to afford the pure compound as a colorless oil.[19]

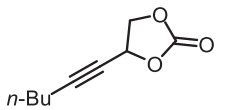
Step 3: To the diol intermediate (1.0 equiv) in DCM (0.25 M) in an argon-flashed flask cooled by an ice bath was added pyridine (4.0 equiv). A solution of triphosgene (BTC, 0.5 equiv) in DCM (0.25 M) was added and the reaction mixture was allowed to stir for 1 h and checked by TLC. The reaction mixture was quenched with saturated aqueous NH_4Cl and diluted with water. The layers were separated, and the aqueous phase was extracted three times with DCM. The combined organic layers were washed with 1 M HCl (three times), saturated aqueous Na_2CO_3 and brine. After separation, the organic layers were dried over Na_2SO_4, filtered, and concentrated *in vacuo*. The crude product was purified by flash chromatography on silica gel (hexanes/ethyl acetate, 20:1) to afford the corresponding cyclic carbonate (note: *the reported yields are based on this three-step sequence*).

4-(4-phenylbut-1-yn-1-yl)-1,3-dioxolan-2-one (**1o**)



Following the **General Procedure A**. Yellowish oil (0.36 g, 42% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.35 – 7.29 (m, 2H), 7.27 – 7.23 (m, 1H), 7.22 – 7.18 (m, 2H), 5.42 – 5.13 (m, 1H), 4.55 (t, *J* = 8.2 Hz, 1H), 4.25 (dd, *J* = 8.3, 6.9 Hz, 1H), 2.85 (t, *J* = 7.4 Hz, 2H), 2.68 – 2.42 (m, 2H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.1, 139.8, 128.5, 128.4, 126.6, 90.8, 74.6, 69.9, 66.6, 34.3, 20.9. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{13}H_{12}NaO_3$ $[M + Na]^+$ 239.0679; Found 239.0669.

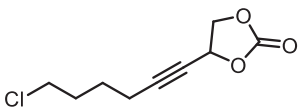
4-(hex-1-yn-1-yl)-1,3-dioxolan-2-one (**1p**)



Following the **General Procedure A**. Yellowish oil (0.73 g, 44% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 5.33 – 5.26 (m, 1H), 4.59 (t, *J* = 8.1 Hz, 1H), 4.32 (dd, *J* = 8.2, 7.0 Hz, 1H), 2.26 (td, *J* = 7.0, 2.0 Hz, 2H), 1.55 – 1.47 (m, 2H), 1.45 – 1.35 (m, 2H), 0.91 (t, *J* = 7.3 Hz, 3H). **^{13}C NMR** (101

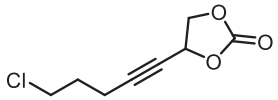
MHz, $CDCl_3$) δ 154.1, 91.8, 73.6, 70.0, 66.7, 30.0, 21.9, 18.4, 13.5. **HRMS** (ESI/TOF) *m/z* Calcd for $C_9H_{12}NaO_3$ $[M + Na]^+$ 191.0679; Found 191.0673.

4-(6-chlorohex-1-yn-1-yl)-1,3-dioxolan-2-one (**1q**)



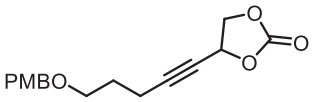
Following the **General Procedure A**. Yellowish oil (0.91 g, 45% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 5.36 – 5.24 (m, 1H), 4.60 (t, *J* = 8.2 Hz, 1H), 4.32 (dd, *J* = 8.3, 6.9 Hz, 1H), 3.55 (t, *J* = 6.4 Hz, 2H), 2.31 (td, *J* = 7.0, 2.0 Hz, 2H), 1.97 – 1.80 (m, 2H), 1.75 – 1.64 (m, 2H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.1, 90.7, 74.3, 69.9, 66.6, 44.3, 31.4, 25.2, 18.0. **HRMS** (ESI/TOF) *m/z* Calcd for $C_9H_{11}ClNaO_3$ $[M + Na]^+$ 225.0289; Found 225.0285.

4-(5-chloropent-1-yn-1-yl)-1,3-dioxolan-2-one (**1r**)



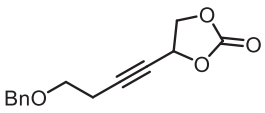
Following the **General Procedure A**. Yellowish oil (0.94 g, 50% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 5.39 – 5.23 (m, 1H), 4.60 (t, *J* = 8.2 Hz, 1H), 4.32 (dd, *J* = 8.3, 6.9 Hz, 1H), 3.62 (t, *J* = 6.2 Hz, 2H), 2.47 (td, *J* = 6.9, 2.0 Hz, 2H), 2.08 – 1.91 (m, 2H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.0, 89.6, 74.7, 69.9, 66.5, 43.3, 30.6, 16.1. **HRMS** (ESI/TOF) *m/z* Calcd for $C_8H_9ClNaO_3$ $[M + Na]^+$ 211.0132; Found 211.0131.

4-(5-((4-methoxybenzyl)oxy)pent-1-yn-1-yl)-1,3-dioxolan-2-one (**1s**)



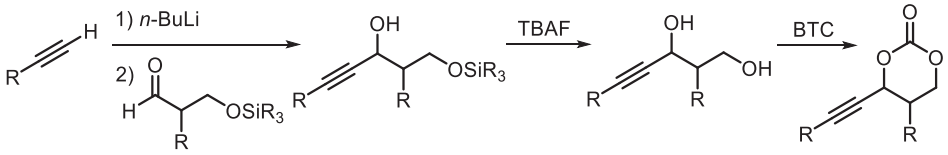
Following the **General Procedure A**. Yellowish oil (1.83 g, 63% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.34 – 7.18 (m, 2H), 6.98 – 6.80 (m, 2H), 5.30 – 5.21 (m, 1H), 4.55 (t, *J* = 8.2 Hz, 1H), 4.43 (s, 2H), 4.26 (dd, *J* = 8.3, 7.0 Hz, 1H), 3.81 (s, 3H), 3.51 (t, *J* = 6.0 Hz, 2H), 2.44 – 2.28 (m, 2H), 1.90 – 1.73 (m, 2H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 159.2, 154.1, 130.4, 129.3, 113.8, 91.1, 73.9, 72.7, 69.9, 68.0, 66.6, 55.3, 28.2, 15.6. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{16}H_{18}NaO_5$ $[M + Na]^+$ 313.1046; Found 313.1049.

4-(4-(benzyloxy)but-1-yn-1-yl)-1,3-dioxolan-2-one (**1t**)



Following the **General Procedure A**. Yellowish oil (1.65 g, 67% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.40 – 7.28 (m, 5H), 5.34 – 5.25 (m, 1H), 4.58 (t, *J* = 8.2 Hz, 1H), 4.55 (s, 2H), 4.32 (dd, *J* = 8.3, 6.9 Hz, 1H), 3.60 (t, *J* = 6.7 Hz, 2H), 2.58 (td, *J* = 6.7, 2.0 Hz, 2H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.0, 137.8, 128.5, 127.9, 127.7, 88.5, 74.7, 73.1, 69.8, 67.5, 66.5, 20.2. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{14}H_{14}NaO_4$ $[M + Na]^+$ 269.0784; Found 269.0784.

General procedure B for the synthesis of *racemic* 6-membered cyclic carbonates:



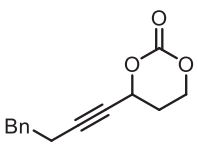
Step 1: To a solution of the alkyne (1.2 equiv) in THF (0.4 M) was added dropwise *n*-BuLi (2.5 M in hexane, 1.2 equiv) at -78 ºC. After the mixture had been stirred for 30 min at the same temperature, the appropriate silyl-protected α-hydroxy carbonyl compound (1.0 equiv), which was prepared following a reported procedure,[20] was added. The reaction mixture was allowed to reach r.t. over 30 min. Upon complete consumption of the carbonyl compound, the reaction was quenched with saturated aqueous NH_4Cl. The organic materials were extracted with EtOAc, and the combined organic extracts were washed with brine, dried over Na_2SO_4, and evaporated in *vacuo*. The crude was purified by flash column chromatography over silica gel (hexanes/ethyl acetate, 10:1) to afford the pure intermediate compound.

Step 2: To a stirred solution of the respective silyl-protected diol (1.0 equiv) in THF (0.4 M) at 0 °C was added tetrabutylammonium fluoride (1.0 M in THF, 1.1 equiv). The flask was warmed to room temperature and stirred until TLC analysis indicated the reaction was complete. The solvent was removed, and the residue was purified by flash column chromatography over silica gel (hexanes/ethyl acetate, 1:1) to afford the unprotected diol.

Step 3: To the diol (1.0 equiv) in DCM (0.25 M) in an argon-flashed flask cooled by an ice bath was added pyridine (4.0 equiv). A solution of triphosgene (BTC, 0.5 equiv) in DCM (0.25 M) was added, and the reaction mixture was allowed to stir for 1 h and checked by TLC. The reaction mixture was quenched with saturated aqueous NH_4Cl and diluted with water. The layers were separated, and the aqueous phase was extracted three times with DCM. The combined organic layers were washed with 1 M HCl (three times), saturated aqueous Na_2CO_3 and brine. After separation, the organic layers were dried over Na_2SO_4, filtered, and concentrated *in vacuo*. The crude product was purified by flash

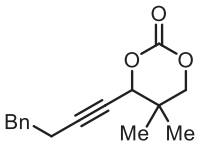
chromatography on silica gel (hexanes/ethyl acetate, 20:1) to afford the corresponding cyclic carbonate (note: *the reported yields are based on the three-step sequence*).

4-(4-phenylbut-1-yn-1-yl)-1,3-dioxan-2-one (**3d**)



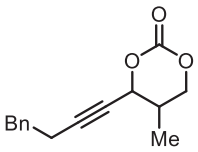
Following the **General Procedure B**. Yellowish oil (0.62 g, 27% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.34 – 7.27 (m, 2H), 7.25 – 7.16 (m, 3H), 5.22 – 5.10 (m, 1H), 4.56 – 4.43 (m, 1H), 4.37 – 4.28 (m, 1H), 2.83 (t, *J* = 7.4 Hz, 2H), 2.55 (td, *J* = 7.4, 2.0 Hz, 2H), 2.35 – 2.22 (m, 1H), 2.06 – 1.95 (m, 1H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 147.6, 140.0, 128.5, 128.4, 126.5, 89.1, 75.9, 68.3, 65.8, 34.4, 27.7, 20.8. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{14}H_{14}NaO_3$ [M + Na]$^+$ 253.0835; Found 253.0835.

5,5-dimethyl-4-(4-phenylbut-1-yn-1-yl)-1,3-dioxan-2-one (**3e**)



Following the **General Procedure B**. Yellowish oil (1.32 g, 51% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34 – 7.28 (m, 2H), 7.25 – 7.18 (m, 3H), 4.78 – 4.66 (m, 1H), 4.12 (d, *J* = 10.8 Hz, 1H), 3.92 (dd, *J* = 10.8, 1.2 Hz, 1H), 2.85 (t, *J* = 7.3 Hz, 2H), 2.66 – 2.53 (m, 2H), 1.08 (s, 3H), 1.02 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 147.5, 140.0, 128.5, 128.4, 126.5, 90.0, 77.5, 75.9, 74.2, 34.4, 32.0, 21.5, 20.6, 19.4. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{16}H_{18}NaO_3$ [M + Na]$^+$ 281.1148; Found 281.1144.

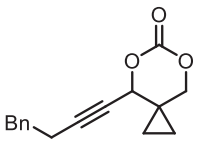
5-methyl-4-(4-phenylbut-1-yn-1-yl)-1,3-dioxan-2-one (**3f**)



Following the **General Procedure B**. Yellowish oil (1.10 g, 45% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.34 – 7.27 (m, 2H), 7.25 – 7.17 (m, 3H), 4.98 (dd, *J* = 4.3, 2.0 Hz, 0.5H), 4.74 (dt, *J* = 7.6, 2.0 Hz, 0.5H), 4.40 (dd, *J* = 11.0, 4.3 Hz, 0.5H), 4.22 – 4.08 (m, 1H), 3.98 (dd, *J* = 11.0, 8.3 Hz, 0.5H), 2.84 (td, *J* = 7.3, 2.1 Hz, 2H), 2.66 – 2.51 (m, 2H), 2.46 – 2.31 (m, 0.5H), 2.23 – 2.10 (m, 0.5H), 1.06 (d, *J* = 6.9 Hz, 1.5H), 0.92 (d, *J* = 6.8 Hz, 1.5H). **^{13}C**

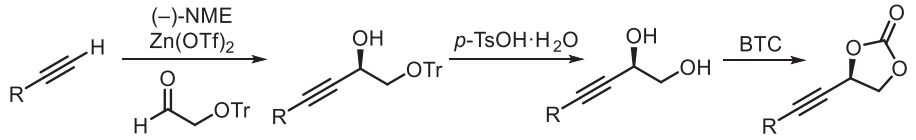
NMR (101 MHz, $CDCl_3$) δ 147.6, 147.6, 140.0, 139.9, 128.5, 128.5, 128.4, 126.5, 126.5, 90.8, 89.1, 75.6, 74.3, 73.6, 72.6, 71.5, 70.6, 34.4, 34.3, 32.4, 30.0, 20.8, 20.6, 12.8, 11.3. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{15}H_{16}NaO_3$ $[M + Na]^+$ 267.0992; Found 267.0991.

4-(4-phenylbut-1-yn-1-yl)-5,7-dioxaspiro[2.5]octan-6-one (**3g**)



Following the **General Procedure B**. Yellowish oil (1.13 g, 44% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.33 – 7.27 (m, 2H), 7.25 – 7.17 (m, 3H), 4.88 – 4.80 (m, 1H), 4.27 (dd, *J* = 11.0, 0.8 Hz, 1H), 4.05 (dt, *J* = 11.0, 0.9 Hz, 1H), 2.83 (t, *J* = 7.3 Hz, 2H), 2.63 – 2.50 (m, 2H), 0.98 – 0.90 (m, 1H), 0.88 – 0.75 (m, 2H), 0.73 – 0.64 (m, 1H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 148.2, 139.9, 128.5, 128.4, 126.5, 89.3, 74.7, 74.0, 73.1, 34.3, 20.7, 18.8, 10.0, 7.4. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{16}H_{16}NaO_3$ $[M + Na]^+$ 279.0992; Found 279.0993.

General procedure C for the synthesis of *chiral* 5-membered cyclic carbonates:



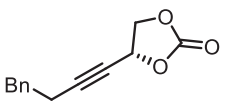
Step 1: $Zn(OTf)_2$ (1.0 equiv) was dried under vacuum at 125 ºC for 2 h. Then the flask was cooled to r.t., the vacuum was released and (–)-*N*-methylephedrine (1.1 equiv.) was added. The vacuum was applied for 30 min and then released. Toluene (1 M) and triethylamine (1.1 equiv) were added, and the reaction mixture was stirred at r.t. for 2 h. The alkyne (1.5 equiv) was added dropwise, and the reaction mixture was stirred at r.t. for 15 min. A solution of the aldehyde (1.1 equiv), which was prepared in accordance with a procedure described in the literature,[21] in toluene (1 M) was added slowly by means of a syringe pump within 1 h. The reaction mixture was stirred until TLC showed complete conversion, and then quenched by the addition of saturated aqueous NH_4Cl. The aqueous layer was extracted with Et_2O, and the combined organic phases were dried over $MgSO_4$, filtered, and concentrated in vacuo. The crude product was purified by flash chromatography on silica gel (hexanes/ethyl acetate, 5:1) to afford the affording the pure, intermediate compound.[21a-b]

Step 2: To a solution of Tr-protected diol (1.0 equiv) in a mixture of DCM and MeOH (0.2 M, 2:1), *p*-TsOH·H_2O (15 mol %) was added. The reaction mixture was stirred until TLC showed complete conversion (typically 16-20 h). Then TEA (15 mol %) and silica gel were added, and the solvent evaporated. The residue was purified by chromatography on a short silica-gel column (hexanes/ethyl acetate, 1:1) to afford the intermediate product.[21a]

Step 3: To the free diol (1.0 equiv) in DCM (0.25 M) in an argon-flashed flask cooled by an ice bath was added pyridine (4.0 equiv). A solution of triphosgene (BTC, 0.5 equiv) in DCM (0.25 M) was added and the reaction mixture was allowed to stir for 1 h and checked by TLC. The reaction mixture was quenched with saturated aqueous NH_4Cl and

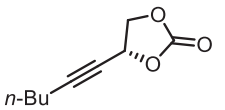
diluted with water. The layers were separated, and the aqueous phase was extracted three times with DCM. The combined organic layers were washed with 1 M HCl (three times), saturated aqueous Na_2CO_3 and brine. After separation, the organic layers were dried over Na_2SO_4, filtered, and concentrated *in vacuo*. The crude product was purified by flash chromatography on silica gel (hexanes/ethyl acetate, 20:1) to afford the corresponding cyclic carbonate (note that *the reported yields are based on the three-step sequence*).

(*R*)-4-(4-phenylbut-1-yn-1-yl)-1,3-dioxolan-2-one (**1o'**)



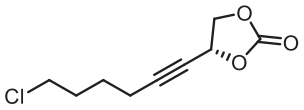
Following the **General Procedure C**. Yellowish oil (0.63 g, 44% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.35 – 7.28 (m, 2H), 7.27 – 7.23 (m, 1H), 7.22 – 7.17 (m, 2H), 5.33 – 5.18 (m, 1H), 4.55 (t, *J* = 8.2 Hz, 1H), 4.25 (dd, *J* = 8.3, 6.9 Hz, 1H), 2.85 (t, *J* = 7.4 Hz, 2H), 2.63 – 2.49 (m, 2H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.1, 139.8, 128.5, 128.4, 126.6, 90.8, 74.6, 69.9, 66.5, 34.3, 20.9. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{13}H_{12}NaO_3$ $[M + Na]^+$ 239.0679; Found 239.0690. **UPC2 conditions**: IA column, isocratic CO_2/MeOH = 90:10, 3 mL/min, 1500 psi. *ee* = 96%, $[\alpha]_D^{25}$ = -3.4 (*c* = 0.12, DCM).

(*R*)-4-(hex-1-yn-1-yl)-1,3-dioxolan-2-one (**1p'**)



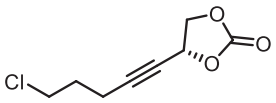
Following the **General Procedure C**. Yellowish oil (0.65 g, 39% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 5.34 – 5.25 (m, 1H), 4.59 (t, *J* = 8.1 Hz, 1H), 4.32 (dd, *J* = 8.2, 7.0 Hz, 1H), 2.26 (td, *J* = 7.1, 2.0 Hz, 2H), 1.56 – 1.46 (m, 2H), 1.45 – 1.35 (m, 2H), 0.91 (t, *J* = 7.3 Hz, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.1, 91.8, 77.3, 77.0, 76.7, 73.6, 70.0, 66.7, 30.0, 21.9, 18.4, 13.5. **HRMS** (ESI/TOF) *m/z* Calcd for $C_9H_{12}NaO_3$ $[M + Na]^+$ 191.0676; Found 191.0679. **UPC2 conditions**: IA column, isocratic CO_2/MeOH = 99:1, 3 mL/min, 1500 psi. *ee* = 87%, $[\alpha]_D^{25}$ = +7.4 (*c* = 0.12, DCM).

(*R*)-4-(6-chlorohex-1-yn-1-yl)-1,3-dioxolan-2-one (**1q'**)



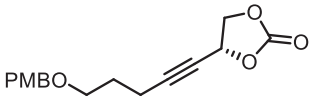
Following the **General Procedure C**. Yellowish oil (0.45 g, 37% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 5.37 – 5.23 (m, 1H), 4.60 (t, *J* = 8.2 Hz, 1H), 4.33 (dd, *J* = 8.3, 6.9 Hz, 1H), 3.56 (t, *J* = 6.4 Hz, 2H), 2.32 (td, *J* = 7.0, 2.0 Hz, 2H), 1.93 – 1.83 (m, 2H), 1.78 – 1.64 (m, 2H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.0, 90.7, 74.3, 69.9, 66.6, 44.3, 31.4, 25.2, 18.1. **HRMS** (ESI/TOF) *m/z* Calcd for $C_9H_{11}ClNaO_3$ $[M + Na]^+$ 225.0289; Found 225.0279. **UPC2 conditions**: IA column, isocratic CO_2/ACN = 90:10, 3 mL/min, 1500 psi. *ee* = 94%, $[\alpha]_D^{25}$ = +7.2 (*c* = 0.16, DCM).

(*R*)-4-(5-chloropent-1-yn-1-yl)-1,3-dioxolan-2-one (**1r'**)



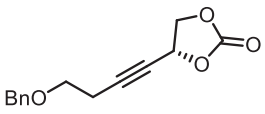
Following the **General Procedure C**. Yellowish oil (0.85 g, 45% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 5.36 – 5.23 (m, 1H), 4.61 (t, *J* = 8.2 Hz, 1H), 4.33 (dd, *J* = 8.3, 6.9 Hz, 1H), 3.63 (t, *J* = 6.2 Hz, 2H), 2.48 (td, *J* = 6.9, 2.0 Hz, 2H), 1.99 (tt, *J* = 6.9, 6.1 Hz, 2H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.0, 89.6, 74.7, 69.9, 66.5, 43.3, 30.6, 16.1. **HRMS** (ESI/TOF) *m/z* Calcd for $C_8H_9ClNaO_3$ $[M + Na]^+$ 211.0132; Found 211.0134. **UPC2 conditions**: IA column, isocratic CO_2/ACN = 97:3, 3 mL/min, 1500 psi. *ee* > 99%, $[\alpha]_D^{25}$ = +7.5 (*c* = 0.13, DCM).

(*R*)-4-(5-((4-methoxybenzyl)oxy)pent-1-yn-1-yl)-1,3-dioxolan-2-one (**1s'**)



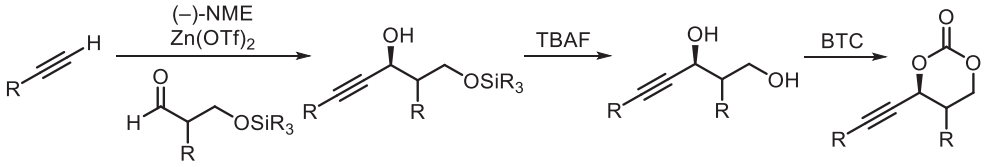
Following the **General Procedure C**. Yellowish oil (1.63 g, 56% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.29 – 7.22 (m, 2H), 6.92 – 6.84 (m, 2H), 5.26 (ddt, *J* = 8.0, 7.0, 2.0 Hz, 1H), 4.55 (t, *J* = 8.1 Hz, 1H), 4.43 (s, 2H), 4.26 (dd, *J* = 8.3, 7.0 Hz, 1H), 3.81 (s, 3H), 3.51 (t, *J* = 6.0 Hz, 2H), 2.38 (td, *J* = 7.1, 2.0 Hz, 2H), 1.81 (tt, *J* = 7.1, 6.0 Hz, 2H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 159.2, 154.1, 130.4, 129.3, 113.8, 91.1, 73.9, 72.7, 69.9, 68.0, 66.6, 55.3, 28.2, 15.6. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{16}H_{18}NaO_5$ $[M + Na]^+$ 313.1046; Found 313.1051. **UPC2 conditions**: IA column, isocratic CO_2/IPA = 90:10, 3 mL/min, 1500 psi. *ee* = 96%, $[\alpha]_D^{25}$ = +1.8 (*c* = 0.16, DCM).

(*R*)-4-(4-(benzyloxy)but-1-yn-1-yl)-1,3-dioxolan-2-one (**1t'**)



Following the **General Procedure C**. Yellowish oil (1.28 g, 52% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.40 – 7.27 (m, 5H), 5.37 – 5.22 (m, 1H), 4.58 (t, *J* = 8.2 Hz, 1H), 4.55 (s, 3H), 4.32 (dd, *J* = 8.3, 6.9 Hz, 1H), 3.59 (t, *J* = 6.7 Hz, 2H), 2.58 (td, *J* = 6.7, 1.9 Hz, 2H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 154.1, 137.8, 128.5, 127.9, 127.7, 88.5, 77.4, 77.0, 76.7, 74.7, 73.1, 69.8, 67.5, 66.5, 20.2. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{14}H_{14}NaO_4$ $[M + Na]^+$ 269.0784; Found 269.0777. **UPC2 conditions**: IA column, isocratic CO_2/MeOH = 90:10, 3 mL/min, 1500 psi. *ee* = 94%, $[\alpha]_D^{25}$ = +2.2 (*c* = 0.15, DCM).

General procedure D for the synthesis of chiral 6-membered cyclic carbonates:



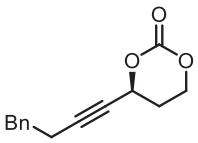
Step 1: $Zn(OTf)_2$ (1.0 equiv) was dried under vacuum at 125 ºC for 2 h. Then the flask was cooled to r.t., the vacuum was released and (–)-*N*-methylephedrine (1.1 equiv.) was added. The vacuum was applied for 30 min and then released. Toluene (1 M) and triethylamine (1.1 equiv) were added, and the reaction mixture was stirred at r.t. for 2 h. The alkyne (1.5 equiv) was added dropwise, and the reaction mixture was stirred at r.t. for 15 min. A solution of aldehyde (1.1 equiv.), which was prepared in accordance with the procedure described in the literature,[11] in toluene (1 M) was added slowly by means of a syringe pump within 1 h. The reaction mixture was stirred until TLC showed complete conversion (typically 16-20 h), then quenched by the addition of saturated aqueous NH_4Cl. The aqueous layer was extracted with Et_2O, and the combined organic phases were dried over $MgSO_4$, filtered, and concentrated in vacuo. The crude product was purified by flash chromatography on silica gel (hexanes/ethyl acetate, 5:1) to afford the affording the pure, intermediate compound.[22a,b]

Step 2: To a stirred solution of the respective silyl-protected diol (1.0 equiv) in THF (0.4 M) at 0 ºC was added tetrabutylammonium fluoride (1.0 M in THF, 1.1 equiv). The flask was warmed to room temperature and stirred until TLC analysis indicated the reaction was complete. The solvent was removed, and the residue was purified by flash column chromatography over silica gel (hexanes/ethyl acetate, 1:1) to afford the diol.

Step 3: To the deprotected diol (1.0 equiv) in DCM (0.25 M) in an argon-flashed flask cooled by an ice bath was added pyridine (4.0 equiv). A solution of triphosgene (BTC, 0.5 equiv) in DCM (0.25 M) was added and the reaction mixture was allowed to stir for 1 h and checked by TLC. The reaction mixture was quenched with saturated aqueous NH_4Cl and diluted with water. The layers were separated, and the aqueous phase was extracted

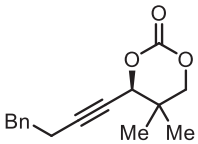
three times with DCM. The combined organic layers were washed with 1 M HCl (three times), saturated aqueous Na_2CO_3 and brine. After separation, the organic layers were dried over Na_2SO_4, filtered, and concentrated *in vacuo*. The crude product was purified by flash chromatography on silica gel (hexanes/ethyl acetate, 20:1) to afford the corresponding cyclic carbonate (note that *the reported yields are based on the three-step sequence*).

(*S*)-4-(4-phenylbut-1-yn-1-yl)-1,3-dioxan-2-one (**3d'**)



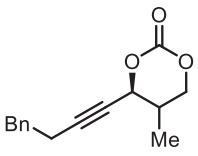
Following the **General Procedure D**. Yellowish oil (0.64 g, 28% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.35 – 7.27 (m, 2H), 7.25 – 7.16 (m, 3H), 5.24 – 5.07 (m, 1H), 4.62 – 4.43 (m, 1H), 4.40 – 4.27 (m, 1H), 2.83 (t, *J* = 7.4 Hz, 2H), 2.55 (td, *J* = 7.2, 2.0 Hz, 2H), 2.36 – 2.22 (m, 1H), 2.07 – 1.94 (m, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 147.6, 140.0, 128.5, 128.4, 126.5, 89.1, 75.9, 68.3, 65.8, 34.4, 27.7, 20.8. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{14}H_{14}NaO_3$ [M + Na]$^+$ 253.0835; Found 253.0831. **UPC2 conditions**: IA column, isocratic CO_2/MeOH = 90:10, 3 mL/min, 1500 psi. *ee* = 88%, $[\alpha]_D^{25}$ = +5.5 (*c* = 0.11, DCM).

(*R*)-5,5-dimethyl-4-(4-phenylbut-1-yn-1-yl)-1,3-dioxan-2-one (**3e'**)



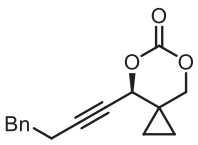
Following the **General Procedure D**. Yellowish oil (1.39 g, 54% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.34 – 7.27 (m, 2H), 7.25 – 7.17 (m, 3H), 4.77 – 4.67 (m, 1H), 4.12 (d, *J* = 10.7 Hz, 1H), 3.92 (dd, *J* = 10.7, 1.2 Hz, 1H), 2.85 (t, *J* = 7.3 Hz, 2H), 2.66 – 2.53 (m, 2H), 1.07 (s, 3H), 1.02 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 147.5, 140.0, 128.5, 128.4, 126.5, 90.0, 77.5, 75.9, 74.2, 34.4, 32.0, 21.5, 20.6, 19.4. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{16}H_{18}NaO_3$ [M + Na]$^+$ 281.1148; Found 281.1144. **UPC2 conditions**: IB column, isocratic CO_2/ACN = 93:7, 3 mL/min, 1500 psi. *ee* = 78%, $[\alpha]_D^{25}$ = +20.3 (*c* = 0.20, DCM).

(4*S*)-5-methyl-4-(4-phenylbut-1-yn-1-yl)-1,3-dioxan-2-one (**3f'**)



Following the **General Procedure D**. Yellowish oil (1.12 g, 46% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.34 – 7.27 (m, 2H), 7.25 – 7.17 (m, 3H), 5.02 – 4.95 (m, 0.5H), 4.74 (dt, *J* = 7.6, 2.0 Hz, 0.5H), 4.40 (dd, *J* = 11.0, 4.3 Hz, 0.5H), 4.20 – 4.09 (m, 1H), 3.98 (dd, *J* = 11.0, 8.3 Hz, 0.5H), 2.84 (td, *J* = 7.4, 2.1 Hz, 2H), 2.65 – 2.51 (m, 2H), 2.46 – 2.33 (m, 0.5H), 2.24 – 2.11 (m, 0.5H), 1.06 (d, *J* = 6.9 Hz, 1.5H), 0.92 (d, *J* = 6.8 Hz, 1.5H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 147.8, 147.7, 140.2, 140.0, 128.6, 128.6, 128.5, 126.7, 126.6, 90.9, 89.2, 75.7, 74.5, 73.7, 72.7, 71.6, 70.7, 34.5, 34.4, 32.5, 30.1, 20.9, 20.8, 12.9, 11.4. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{15}H_{16}NaO_3$ $[M + Na]^+$ 267.0992; Found 267.0991. **UPC2 conditions**: IA column, isocratic CO_2/MeOH = 90:10, 3 mL/min, 1500 psi. *ee* = 98%, $[\alpha]_D^{25}$ = +28.9 (*c* = 0.16, DCM).

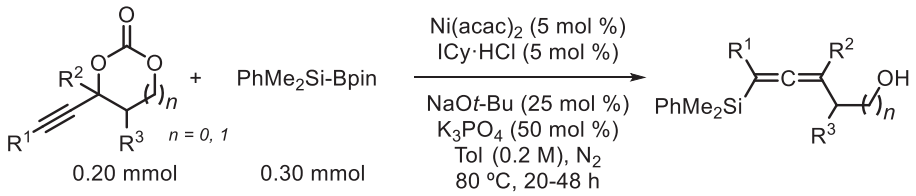
(*R*)-4-(4-phenylbut-1-yn-1-yl)-5,7-dioxaspiro[2.5]octan-6-one (**3g'**)



Following the **General Procedure D**. Yellowish oil (1.26 g, 49% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.33 – 7.27 (m, 2H), 7.25 – 7.17 (m, 3H), 4.89 – 4.78 (m, 1H), 4.26 (dd, *J* = 11.0, 0.8 Hz, 1H), 4.05 (dt, *J* = 11.0, 0.9 Hz, 1H), 2.83 (t, *J* = 7.3 Hz, 2H), 2.62 – 2.49 (m, 2H), 0.98 – 0.91 (m, 1H), 0.87 – 0.74 (m, 2H), 0.73 – 0.66 (m, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 148.2, 139.9, 128.5, 128.4, 126.5, 89.3, 74.7, 74.0, 73.1, 34.3, 20.7, 18.8, 10.0, 7.4. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{16}H_{16}NaO_3$ $[M + Na]^+$ 279.0992; Found 279.1001. **UPC2 conditions**: OJ column, isocratic CO_2/EtOH = 92:8, 2 mL/min, 2000 psi. *ee* = 84%, $[\alpha]_D^{25}$ = +75.3 (*c* = 0.11, DCM).

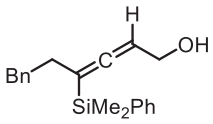
4.5.3 General procedure for the synthesis of the silylated allenols

General Procedure E:



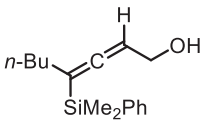
In a N_2-filled glove box, a dried 2 mL vial was charged with the respective cyclic carbonate (1.0 equiv), $PhMe_2Si$-Bpin (1.5 equiv), NaO*t*-Bu (25 mol %), ICy·HCl (5 mol %), $Ni(acac)_2$ (5 mol %), K_3PO_4 (50 mol %), and toluene (0.2 M). The reaction mixture was stirred at 80 ºC until TLC analysis indicated that the reaction was complete (*the reaction mixture can be open to the air when doing the TLC analysis*). Hereafter, the solvent was evaporated by a gentle stream of N_2, and the residue was purified by flash chromatography on silica gel (hexanes/ethyl acetate, 20:1) to afford all corresponding products as oils.

4-(dimethyl(phenyl)silyl)-6-phenylhexa-2,3-dien-1-ol (**2o**)



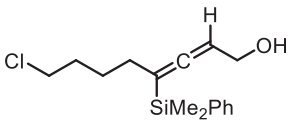
Following the **General Procedure E**. Yellowish oil (41.3 mg, 67% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.57 – 7.52 (m, 2H), 7.43 – 7.37 (m, 3H), 7.31 – 7.25 (m, 2H), 7.23 – 7.17 (m, 1H), 7.16 – 7.10 (m, 2H), 5.14 – 5.03 (m, 1H), 4.03 – 3.87 (m, 2H), 2.81 – 2.68 (m, 2H), 2.40 – 2.24 (m, 2H), 0.94 (s, 1H), 0.42 (s, 6H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.7, 141.9, 137.7, 133.9, 129.4, 128.5, 128.3, 127.9, 125.9, 97.2, 87.5, 61.2, 35.1, 30.5, -3.0, -3.2. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.6. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{20}H_{24}NaOSi$ $[M + Na]^+$ 331.1489; Found 331.1487.

4-(dimethyl(phenyl)silyl)octa-2,3-dien-1-ol (**2p**)



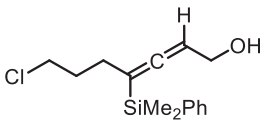
Following the **General Procedure E**. Yellowish oil (43.8 mg, 84% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.57 – 7.51 (m, 2H), 7.39 – 7.35 (m, 3H), 5.07 (tt, *J* = 6.6, 3.0 Hz, 1H), 4.04 (d, *J* = 6.6 Hz, 2H), 2.02 – 1.94 (m, 2H), 1.47 – 1.36 (m, 2H), 1.35 – 1.25 (m, 2H), 1.20 – 1.09 (m, 1H), 0.86 (t, *J* = 7.2 Hz, 3H), 0.41 (s, 6H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.5, 137.9, 133.8, 129.2, 127.8, 97.8, 86.8, 61.4, 31.2, 29.0, 22.3, 13.9, -2.9, -3.1. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.4. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{16}H_{24}NaOSi$ $[M + Na]^+$ 283.1489; Found 283.1482.

8-chloro-4-(dimethyl(phenyl)silyl)octa-2,3-dien-1-ol (**2q**)



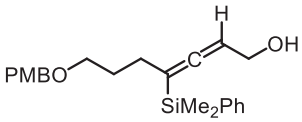
Following the **General Procedure E**. Yellowish oil (47.2 mg, 80% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.55 – 7.49 (m, 2H), 7.39 – 7.35 (m, 3H), 5.13 – 5.06 (m, 1H), 4.05 (d, *J* = 6.6 Hz, 2H), 3.47 (t, *J* = 6.7 Hz, 2H), 2.02 – 1.96 (m, 2H), 1.80 – 1.70 (m, 2H), 1.61 – 1.51 (m, 2H), 1.15 (s, 1H), 0.40 (s, 6H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.5, 137.6, 133.8, 129.3, 127.9, 97.3, 87.3, 61.3, 44.9, 32.0, 28.4, 26.1, -3.0, -3.2. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ –8.6. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{16}H_{23}ClNaOSi$ $[M + Na]^+$ 317.1099; Found 317.1091.

7-chloro-4-(dimethyl(phenyl)silyl)hepta-2,3-dien-1-ol (**2r**)



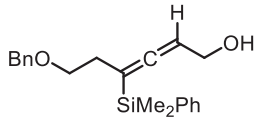
Following the **General Procedure E**. Yellowish oil (44.9 mg, 80% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.56 – 7.51 (m, 2H), 7.41 – 7.35 (m, 3H), 5.21 – 5.03 (m, 1H), 4.05 (d, *J* = 6.6 Hz, 2H), 3.52 (t, *J* = 6.5 Hz, 2H), 2.18 – 2.07 (m, 2H), 1.99 – 1.80 (m, 2H), 1.33 (s, 1H), 0.41 (s, 6H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.4, 137.5, 133.8, 129.4, 127.9, 96.6, 87.6, 61.2, 44.4, 31.7, 26.3, -3.0, -3.2. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.1. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{15}H_{21}ClNaOSi$ $[M + Na]^+$ 303.0942; Found 303.0938. The spectral data was identical to those reported in the literature.[9]

4-(dimethyl(phenyl)silyl)-7-((4-methoxybenzyl)oxy)hepta-2,3-dien-1-ol (**2s**)



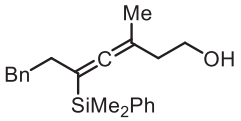
Following the **General Procedure E**. Yellowish oil (49.7 mg, 65% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.56 – 7.51 (m, 2H), 7.41 – 7.34 (m, 3H), 7.25 – 7.21 (m, 2H), 6.93 – 6.83 (m, 2H), 5.17 – 5.01 (m, 1H), 4.39 (s, 2H), 4.02 (d, *J* = 6.6 Hz, 2H), 3.81 (s, 3H), 3.43 (t, *J* = 6.5 Hz, 2H), 2.11 – 2.00 (m, 2H), 1.81 – 1.69 (m, 2H), 1.52 (s, 1H), 0.40 (s, 6H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.5, 159.2, 137.8, 133.8, 130.6, 129.3, 127.8, 113.8, 97.4, 87.5, 72.5, 69.4, 61.2, 55.3, 28.9, 25.7, -3.0, -3.1. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.4. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{23}H_{30}NaO_3Si$ $[M + Na]^+$ 405.1856; Found 405.1852.

6-(benzyloxy)-4-(dimethyl(phenyl)silyl)hexa-2,3-dien-1-ol (**2t**)



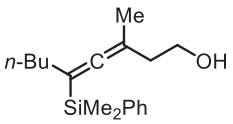
Following the **General Procedure E**. Yellowish oil (44.0 mg, 65% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.59 – 7.53 (m, 2H), 7.42 – 7.28 (m, 8H), 5.17 – 5.08 (m, 1H), 4.45 (s, 2H), 4.09 – 3.99 (m, 2H), 3.64 – 3.56 (m, 1H), 3.54 – 3.46 (m, 1H), 2.35 – 2.25 (m, 2H), 1.84 (s, 1H), 0.42 (s, 3H), 0.41 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.8, 138.2, 137.6, 133.9, 129.3, 128.4, 127.9, 127.8, 127.7, 95.0, 87.4, 72.8, 69.2, 60.4, 29.4, -3.0, -3.2. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.4. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{21}H_{26}NaO_2Si$ $[M + Na]^+$ 361.1594; Found 361.1596.

5-(dimethyl(phenyl)silyl)-3-methyl-7-phenylhepta-3,4-dien-1-ol (**4a**)



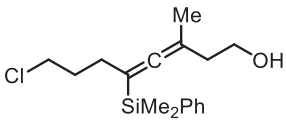
Following the **General Procedure E**. Yellowish oil (55.2 mg, 82% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.58 – 7.52 (m, 2H), 7.42 – 7.36 (m, 3H), 7.30 – 7.24 (m, 2H), 7.20 – 7.11 (m, 3H), 3.60 (t, *J* = 6.4 Hz, 2H), 2.77 – 2.68 (m, 2H), 2.33 – 2.23 (m, 2H), 2.20 – 2.10 (m, 2H), 1.65 (s, 3H), 1.40 (s, 1H), 0.40 (s, 3H), 0.39 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.3, 142.2, 138.1, 133.9, 129.2, 128.4, 128.3, 127.8, 125.7, 95.4, 91.8, 60.9, 36.9, 35.5, 31.5, 18.7, -2.8, -2.8. The spectral data was identical to those reported in the literature.[24]

5-(dimethyl(phenyl)silyl)-3-methylnona-3,4-dien-1-ol (**4b**)



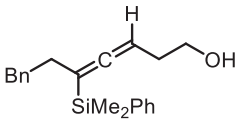
Following the **General Procedure E**. Yellowish oil (36.9 mg, 64% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.56 – 7.49 (m, 2H), 7.40 – 7.32 (m, 3H), 3.63 (t, *J* = 6.3 Hz, 2H), 2.22 – 2.10 (m, 2H), 1.97 – 1.90 (m, 2H), 1.67 (s, 3H), 1.54 (s, 1H), 1.43 – 1.33 (m, 2H), 1.32 – 1.23 (m, 2H), 0.85 (t, *J* = 7.2 Hz, 3H), 0.36 (s, 3H), 0.36 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 205.1, 138.4, 133.8, 129.0, 127.7, 95.8, 90.9, 60.9, 36.9, 31.5, 29.6, 22.4, 18.7, 14.0, -2.7, -2.8. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.1. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{18}H_{28}NaOSi$ $[M + Na]^+$ 311.1802; Found 311.1810.

8-chloro-5-(dimethyl(phenyl)silyl)-3-methylocta-3,4-dien-1-ol (**4c**)



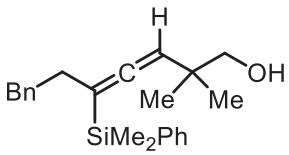
Following the **General Procedure E**. Yellowish oil (51.3 mg, 83% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.55 – 7.48 (m, 2H), 7.40 – 7.33 (m, 3H), 3.63 (t, *J* = 6.4 Hz, 2H), 3.50 (t, *J* = 6.6 Hz, 2H), 2.23 – 2.12 (m, 2H), 2.12 – 2.03 (m, 2H), 1.93 – 1.80 (m, 2H), 1.68 (s, 3H), 1.42 (s, 1H), 0.38 (s, 3H), 0.37 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 205.1, 137.9, 133.8, 129.2, 127.8, 94.5, 91.9, 60.8, 44.6, 36.9, 32.0, 26.9, 18.6, -2.8, -2.9. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.1. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{17}H_{25}ClNaOSi$ $[M + Na]^+$ 331.1255; Found 331.1255.

5-(dimethyl(phenyl)silyl)-7-phenylhepta-3,4-dien-1-ol (**4d**)



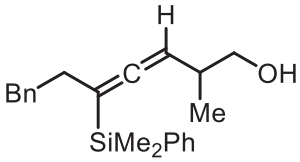
Following the **General Procedure E**. Yellowish oil (15.5 mg, 24% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.55 – 7.49 (m, 2H), 7.40 – 7.34 (m, 3H), 7.27 – 7.22 (m, 2H), 7.19 – 7.14 (m, 1H), 7.13 – 7.09 (m, 2H), 4.94 – 4.78 (m, 1H), 3.58 (t, *J* = 6.4 Hz, 2H), 2.79 – 2.64 (m, 2H), 2.28 – 2.21 (m, 2H), 2.18 (q, *J* = 6.5 Hz, 2H), 1.31 (s, 1H), 0.38 (s, 3H), 0.38 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 207.1, 142.1, 137.8, 133.9, 129.2, 128.5, 128.2, 127.8, 125.8, 95.4, 82.8, 62.5, 35.3, 32.0, 31.1, -2.9, -3.1. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.8. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{21}H_{26}NaOSi$ $[M + Na]^+$ 345.1645; Found 345.1645.

5-(dimethyl(phenyl)silyl)-2,2-dimethyl-7-phenylhepta-3,4-dien-1-ol (**4e**)



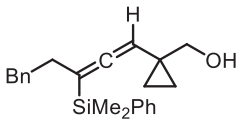
Following the **General Procedure E**. Yellowish oil (46.3 mg, 66% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.58 – 7.53 (m, 2H), 7.42 – 7.36 (m, 3H), 7.29 – 7.24 (m, 2H), 7.21 – 7.16 (m, 1H), 7.15 – 7.11 (m, 2H), 4.82 (t, *J* = 3.2 Hz, 1H), 3.29 (s, 2H), 2.81 – 2.63 (m, 2H), 2.31 – 2.21 (m, 2H), 1.37 (s, 1H), 1.01 (s, 3H), 0.99 (s, 3H), 0.42 (s, 3H), 0.41 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.0, 142.2, 137.7, 134.0, 129.3, 128.4, 128.3, 127.9, 125.8, 97.3, 94.5, 72.3, 37.1, 35.5, 31.4, 24.8, -2.9, -3.0. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.8. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{23}H_{30}NaOSi$ $[M + Na]^+$ 373.1958; Found 373.1957.

5-(dimethyl(phenyl)silyl)-2-methyl-7-phenylhepta-3,4-dien-1-ol (**4f**)



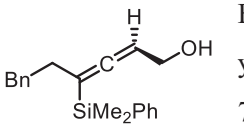
Following the **General Procedure E**. Yellowish oil (38.4 mg, 57% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.57 – 7.52 (m, 2H), 7.42 – 7.35 (m, 3H), 7.29 – 7.23 (m, 2H), 7.20 – 7.15 (m, 1H), 7.15 – 7.10 (m, 2H), 4.93 – 4.81 (m, 1H), 3.47 – 3.37 (m, 2H), 2.77 – 2.66 (m, 2H), 2.36 – 2.27 (m, 1H), 2.27 – 2.21 (m, 2H), 1.40 (s, 1H), 0.99 (dd, *J* = 8.5, 6.9 Hz, 3H), 0.40 (s, 3H), 0.40 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 206.0, 205.9, 142.2, 137.8, 137.7, 133.9, 129.2, 128.4, 128.3, 127.9, 125.8, 96.5, 96.3, 89.3, 89.2, 68.0, 36.2, 36.0, 35.4, 35.4, 31.3, 31.2, 17.0, 16.8, -2.9, -3.1. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -9.0. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{22}H_{28}NaOSi$ $[M + Na]^+$ 359.1802; Found 359.1802.

(1-(3-(dimethyl(phenyl)silyl)-5-phenylpenta-1,2-dien-1-yl)cyclopropyl)methanol (**4g**)



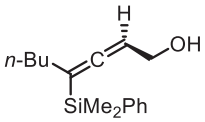
Following the **General Procedure E**. Yellowish oil (39.0 mg, 56% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.58 – 7.52 (m, 2H), 7.41 – 7.36 (m, 3H), 7.29 – 7.23 (m, 2H), 7.21 – 7.15 (m, 1H), 7.15 – 7.10 (m, 2H), 5.00 (t, *J* = 3.1 Hz, 1H), 3.44 (s, 2H), 2.79 – 2.64 (m, 2H), 2.34 – 2.18 (m, 2H), 1.37 (s, 1H), 0.67 – 0.62 (m, 2H), 0.58 – 0.53 (m, 2H), 0.41 (s, 3H), 0.40 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.7, 142.1, 137.7, 133.9, 129.3, 128.4, 128.3, 127.9, 125.8, 98.4, 91.2, 69.3, 35.3, 31.3, 21.7, 12.0, 11.8, -2.9, -3.1. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -9.2. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{23}H_{28}NaOSi$ $[M + Na]^+$ 371.1802; Found 371.1794.

4-(dimethyl(phenyl)silyl)-6-phenylhexa-2,3-dien-1-ol (**2o'**)



Following the **General Procedure E**. Yellowish oil (46.3 g, 75% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.59 – 7.52 (m, 2H), 7.43 – 7.36 (m, 3H), 7.31 – 7.25 (m, 2H), 7.23 – 7.17 (m, 1H), 7.16 – 7.10 (m, 2H), 5.14 – 5.03 (m, 1H), 4.03 – 3.89 (m, 2H), 2.81 – 2.69 (m, 2H), 2.39 – 2.26 (m, 2H), 0.95 (s, 1H), 0.42 (s, 6H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.7, 141.9, 137.7, 133.9, 129.4, 128.5, 128.3, 127.9, 125.9, 97.2, 87.5, 61.2, 35.1, 30.5, -3.0, -3.2. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.3. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{20}H_{24}NaOSi$ $[M + Na]^+$ 331.1489; Found 331.1483. **UPC2 conditions**: OJ column, isocratic CO_2/ACN = 95:5, 2 mL/min, 2000 psi. *ee* = 93%, *es* = 97%, $[\alpha]_D^{25}$ = -2.1 (*c* = 0.15, DCM).

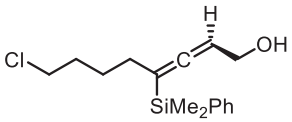
4-(dimethyl(phenyl)silyl)octa-2,3-dien-1-ol (**2p'**)



Following the **General Procedure E**. Yellowish oil (42.7 mg, 82% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.57 – 7.52 (m, 2H), 7.39 – 7.36 (m, 3H), 5.10 – 5.03 (m, 1H), 4.04 (d, *J* = 6.7 Hz, 2H), 2.02 – 1.93 (m, 2H), 1.46 – 1.36 (m, 2H), 1.35 – 1.26 (m, 2H), 0.86 (t, *J* = 7.2 Hz, 3H), 0.40 (s, 6H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.5, 137.9, 133.8, 129.2, 127.8, 97.8, 86.8, 61.4, 31.2, 29.0, 22.3, 13.9, -2.9, -3.1. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.4. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{16}H_{24}NaOSi$ $[M + Na]^+$ 283.1489; Found 283.1484. **UPC2 conditions**: IG column,

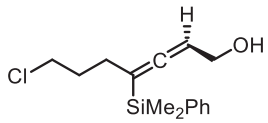
isocratic CO_2/MeOH = 98:2, 2 mL/min, 2000 psi. *ee* = 89%, *es* > 99%, $[\alpha]_D^{25}$ = -5.1 (*c* = 0.14, DCM).

8-chloro-4-(dimethyl(phenyl)silyl)octa-2,3-dien-1-ol (**2q'**)



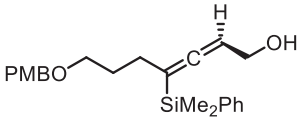
Following the **General Procedure E**. Yellowish oil (43.6 mg, 74% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.56 – 7.50 (m, 2H), 7.41 – 7.36 (m, 3H), 5.15 – 5.05 (m, 1H), 4.06 (d, *J* = 6.6 Hz, 2H), 3.47 (t, *J* = 6.7 Hz, 2H), 2.04 – 1.95 (m, 2H), 1.80 – 1.69 (m, 2H), 1.62 – 1.51 (m, 2H), 1.22 (s, 1H), 0.40 (s, 6H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.5, 137.6, 133.8, 129.3, 127.9, 97.3, 87.3, 61.3, 44.9, 32.0, 28.4, 26.2, -3.0, -3.1. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.6. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{16}H_{23}ClNaOSi$ $[M + Na]^+$ 317.1099; Found 317.1101. **UPC2 conditions**: IG column, isocratic CO_2/MeOH = 95:5, 2 mL/min, 2000 psi. *ee* = 93%, *es* = 99%, $[\alpha]_D^{25}$ = -6.3 (*c* = 0.12, DCM).

7-chloro-4-(dimethyl(phenyl)silyl)hepta-2,3-dien-1-ol (**2r'**)



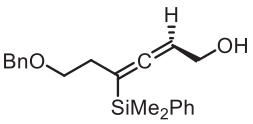
Following the **General Procedure E**. Yellowish oil (38.8 mg, 69% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.55 – 7.50 (m, 2H), 7.41 – 7.34 (m, 3H), 5.17 – 5.06 (m, 1H), 4.05 (d, *J* = 6.5 Hz, 2H), 3.51 (t, *J* = 6.5 Hz, 2H), 2.16 – 2.08 (m, 2H), 1.95 – 1.83 (m, 2H), 1.19 (s, 1H), 0.41 (s, 6H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.4, 137.5, 133.8, 129.4, 127.9, 96.7, 87.6, 61.2, 44.4, 31.7, 26.3, -3.1, -3.2. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.4. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{15}H_{21}ClNaOSi$ $[M + Na]^+$ 303.0942; Found 303.0943. **UPC2 conditions**: IG column, isocratic CO_2/MeOH = 96:4, 2 mL/min, 2000 psi. *ee* = 94%, *es* = 94%, $[\alpha]_D^{25}$ = -9.1 (*c* = 0.12, DCM).

4-(dimethyl(phenyl)silyl)-7-((4-methoxybenzyl)oxy)hepta-2,3-dien-1-ol (**2s'**)



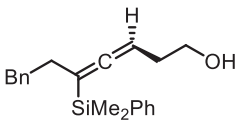
Following the **General Procedure E**. Yellowish oil (52.0 mg, 68% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.56 – 7.51 (m, 2H), 7.40 – 7.34 (m, 3H), 7.26 – 7.21 (m, 2H), 6.90 – 6.85 (m, 2H), 5.13 – 5.03 (m, 1H), 4.39 (s, 2H), 4.02 (d, *J* = 6.6 Hz, 2H), 3.81 (s, 3H), 3.43 (t, *J* = 6.5 Hz, 2H), 2.12 – 1.99 (m, 2H), 1.83 – 1.70 (m, 2H), 1.59 (s, 1H), 0.40 (s, 6H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.5, 159.2, 137.8, 133.8, 130.6, 129.3, 127.8, 113.8, 97.4, 87.5, 72.5, 69.4, 61.2, 55.3, 28.9, 25.7, -3.0, -3.1. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.7. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{23}H_{30}NaO_3Si$ $[M + Na]^+$ 405.1856; Found 405.1853. **UPC2 conditions**: IG column, isocratic CO_2/MeOH = 85:15, 2 mL/min, 2000 psi. *ee* = 94%, *es* = 98%, $[\alpha]_D^{25}$ = -8.5 (*c* = 0.11, DCM).

6-(benzyloxy)-4-(dimethyl(phenyl)silyl)hexa-2,3-dien-1-ol (**2t'**)



Following the **General Procedure E**. Yellowish oil (46.0 mg, 68% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.58 – 7.53 (m, 2H), 7.41 – 7.28 (m, 8H), 5.17 – 5.08 (m, 1H), 4.45 (s, 2H), 4.09 – 3.99 (m, 2H), 3.64 – 3.57 (m, 1H), 3.54 – 3.46 (m, 1H), 2.34 – 2.26 (m, 2H), 1.85 (s, 1H), 0.42 (s, 3H), 0.41 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.8, 138.2, 137.6, 133.9, 129.3, 128.4, 127.9, 127.8, 127.7, 95.0, 87.4, 72.8, 69.2, 60.4, 29.4, -3.0, -3.2. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.2. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{21}H_{26}NaO_2Si$ $[M + Na]^+$ 361.1594; Found 361.1592. **UPC2 conditions**: IG column, isocratic CO_2/MeOH = 85:15, 2 mL/min, 2000 psi. *ee* = 88%, *es* = 94%, $[\alpha]_D^{25}$ = -8.6 (*c* = 0.15, DCM).

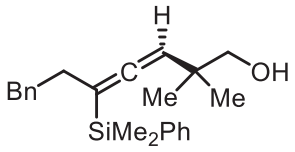
5-(dimethyl(phenyl)silyl)-7-phenylhepta-3,4-dien-1-ol (**4d'**)



Following the **General Procedure E**. Yellowish oil (18.7 mg, 29% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.56 – 7.51 (m, 2H), 7.41 – 7.35 (m, 3H), 7.29 – 7.22 (m, 2H), 7.20 – 7.14 (m, 1H), 7.14 – 7.09 (m, 2H), 4.93 – 4.80 (m, 1H), 3.58 (t, *J* = 6.4 Hz, 2H), 2.79 – 2.65 (m, 2H), 2.28 – 2.22 (m, 2H), 2.19 (q, *J* = 6.5 Hz, 2H), 1.37 (s, 1H), 0.39 (s, 3H), 0.39 (s, 3H). **^{13}C NMR** (101 MHz,

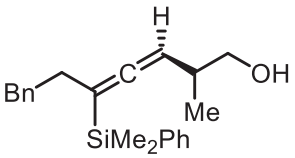
$CDCl_3$) δ 207.1, 142.1, 137.8, 133.9, 129.2, 128.5, 128.2, 127.8, 125.8, 95.4, 82.8, 62.5, 35.3, 32.0, 31.1, -2.9, -3.1. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.8. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{21}H_{26}NaOSi$ $[M + Na]^+$ 345.1645; Found 345.1647. **UPC2 conditions**: OJ column, isocratic CO_2/ACN = 90:10, 2 mL/min, 2000 psi. *ee* = 77%, *es* = 88%, $[\alpha]_D^{25}$ = -3.4 (*c* = 0.12, DCM).

5-(dimethyl(phenyl)silyl)-2,2-dimethyl-7-phenylhepta-3,4-dien-1-ol (**4e'**)



Following the **General Procedure E**. Yellowish oil (50.5 mg, 72% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.57 – 7.52 (m, 2H), 7.41 – 7.35 (m, 3H), 7.29 – 7.23 (m, 2H), 7.21 – 7.15 (m, 1H), 7.15 – 7.11 (m, 2H), 4.82 (t, *J* = 3.2 Hz, 1H), 3.29 (d, *J* = 0.8 Hz, 2H), 2.82 – 2.61 (m, 2H), 2.30 – 2.20 (m, 2H), 1.41 (s, 1H), 1.00 (s, 3H), 0.99 (s, 3H), 0.41 (s, 3H), 0.40 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.0, 142.2, 137.7, 134.0, 129.3, 128.4, 128.3, 127.9, 125.8, 97.3, 94.5, 77.4, 77.1, 76.7, 72.3, 37.1, 35.4, 31.4, 24.8, -2.9, -3.0. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -9.0. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{23}H_{30}NaOSi$ $[M + Na]^+$ 373.1958; Found 373.1964. **UPC2 conditions**: OJ column, isocratic CO_2/ACN = 85:15, 2 mL/min, 2000 psi. *ee* = 68%, *es* = 87%, $[\alpha]_D^{25}$ = -1.6 (*c* = 0.13, DCM).

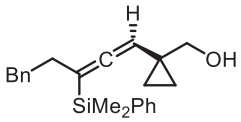
(2*R*)-5-(dimethyl(phenyl)silyl)-2-methyl-7-phenylhepta-3,4-dien-1-ol (**4f'**)



Following the **General Procedure E**. Yellowish oil (31.6 mg, 47% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.56 – 7.50 (m, 2H), 7.40 – 7.34 (m, 3H), 7.28 – 7.22 (m, 2H), 7.19 – 7.14 (m, 1H), 7.14 – 7.10 (m, 2H), 4.94 – 4.76 (m, 1H), 3.50 – 3.34 (m, 2H), 2.78 – 2.64 (m, 2H), 2.35 – 2.27 (m, 1H), 2.27 – 2.21 (m, 2H), 1.35 (s, 1H), 0.98 (dd, *J* = 8.4, 6.8 Hz, 3H), 0.40 (s, 3H), 0.39 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.9, 205.9, 142.2, 137.8, 137.7, 133.9, 129.2, 128.4, 128.3, 127.8, 125.8, 96.5, 96.3, 89.3, 89.2, 68.0, 36.2, 36.0, 35.4, 35.4, 31.3, 31.2, 17.0, 16.8, -2.9, -3.1. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -9.0. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{22}H_{28}NaOSi$ $[M + Na]^+$ 359.1802; Found

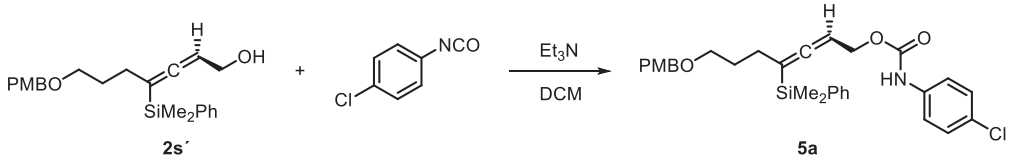
359.1810. **UPC2 conditions**: OJ column, isocratic CO_2/ACN = 90:10, 2 mL/min, 2000 psi. *ee* = 87%, *es* = 89%, $[\alpha]_D^{25}$ = -3.4 (*c* = 0.13, DCM).

(1-(3-(dimethyl(phenyl)silyl)-5-phenylpenta-1,2-dien-1-yl)cyclopropyl)methanol (**4g'**)



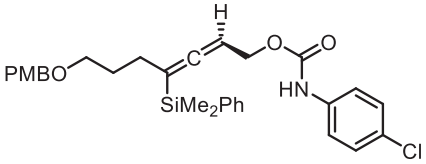
Following the **General Procedure E**. Yellowish oil (45.3 mg, 65% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.58 – 7.52 (m, 2H), 7.41 – 7.37 (m, 3H), 7.29 – 7.24 (m, 2H), 7.21 – 7.15 (m, 1H), 7.15 – 7.11 (m, 2H), 5.01 (t, *J* = 3.1 Hz, 1H), 3.44 (d, *J* = 1.1 Hz, 2H), 2.80 – 2.65 (m, 2H), 2.35 – 2.20 (m, 2H), 1.38 (s, 1H), 0.67 – 0.62 (m, 2H), 0.58 – 0.53 (m, 2H), 0.41 (s, 3H), 0.41 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.7, 142.2, 137.7, 133.9, 129.3, 128.4, 128.3, 127.9, 125.8, 98.4, 91.2, 69.3, 35.3, 31.3, 21.7, 12.0, 11.8, -2.9, -3.1. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -9.2. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{23}H_{28}NaOSi$ $[M + Na]^+$ 371.1802; Found 371.1800. **UPC2 conditions**: OJ column, isocratic CO_2/ACN = 90:10, 2 mL/min, 2000 psi. *ee* = 53%, *es* = 63%, $[\alpha]_D^{25}$ = -4.7 (*c* = 0.14, DCM).

4.5.4 Procedures for the post-modifications of compound 2s´

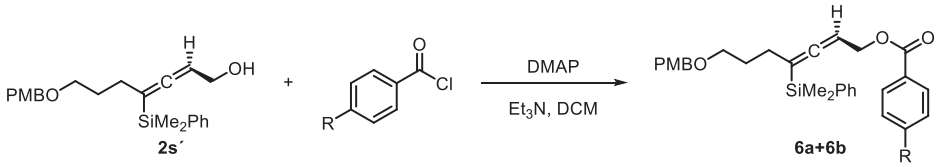


To a solution of the silyl allenol **2s´** (0.3 mmol, 114.8 mg, 1.0 equiv) in DCM (0.6 mL, 0.5 M) was added 4-4-chlorophenyl isocyanate (0.36 mmol, 71.3 mg, 1.2 equiv) at r.t., followed by Et_3N (0.6 mmol, 60.7 mg, 2.0 equiv). The reaction mixture was stirred for 12 h and TLC analysis then indicated the reaction was complete. Hereafter, the solvent was evaporated by a gentle stream of N_2, and the residue was purified by flash chromatography on silica gel (hexanes/ethyl acetate, 5:1) to afford the corresponding product **5a** as an oil.

(*R*)-4-(dimethyl(phenyl)silyl)-7-((4-methoxybenzyl)oxy)hepta-2,3-dien-1-yl (4-chlorophenyl)carbamate (**5a**)

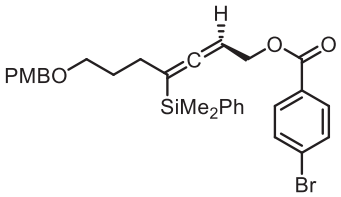


Yellowish oil (135.8 mg, 85% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.53 – 7.48 (m, 2H), 7.39 – 7.31 (m, 3H), 7.29 – 7.26 (m, 2H), 7.25 – 7.18 (m, 4H), 6.87 – 6.83 (m, 2H), 6.68 (s, 1H), 5.14 – 5.05 (m, 1H), 4.66 – 4.54 (m, 2H), 4.37 (s, 2H), 3.79 (s, 3H), 3.41 (td, *J* = 6.6, 1.6 Hz, 2H), 2.05 – 1.97 (m, 2H), 1.74 (p, *J* = 7.0 Hz, 2H), 1.64 (s, 1H), 0.38 (s, 3H), 0.38 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 206.6, 159.2, 153.2, 137.4, 136.6, 133.8, 130.6, 129.3, 129.3, 129.0, 128.3, 127.8, 119.8, 113.8, 97.2, 82.8, 72.5, 69.4, 63.9, 55.3, 28.8, 25.4, -3.1, -3.2. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.6. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{30}H_{34}ClNNaO_4Si$ $[M + Na]^+$ 558.1838; Found 558.1848.



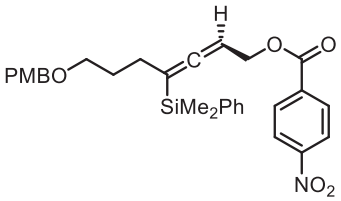
To an oven dried flask charged with a stirring bar and dry DCM (2 mL, 0.15 M) was added the silyl allenol **2s´** (0.3 mmol, 114.8 mg, 1.0 equiv) and the mixture was cooled to 0 ºC via an ice/water bath. Then 4-dimethylaminopyridine (DMAP, 0.03 mmol, 3.7 mg, 10 mol %) was added, followed by the dropwise addition of dry Et_3N (0.9 mmol, 91.1 mg, 3.0 equiv). After this mixture had been stirred for ~5-10 min, the respective benzoyl chloride (0.45 mmol, 1.5 equiv: for R = Br, 98.8 mg; for R = NO_2, 83.5 mg) was slowly added and the resulting solution was stirred while warming to r.t. for 12 h. TLC analysis indicated the reaction was complete. Hereafter, the solvent was evaporated by a gentle stream of N_2, and the residue was purified by flash chromatography on silica gel (hexanes/ethyl acetate, 5:1) to afford the corresponding product as an oil.

(*R*)-4-(dimethyl(phenyl)silyl)-7-((4-methoxybenzyl)oxy)hepta-2,3-dien-1-yl 4-bromo benzoate (**6a**)



Yellowish oil (132.5 mg, 78% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.91 – 7.85 (m, 2H), 7.58 – 7.53 (m, 2H), 7.52 – 7.47 (m, 2H), 7.38 – 7.29 (m, 3H), 7.23 – 7.16 (m, 2H), 6.89 – 6.82 (m, 2H), 5.20 – 5.12 (m, 1H), 4.79 – 4.72 (m, 2H), 4.36 (s, 2H), 3.80 (s, 3H), 3.40 (t, *J* = 6.5 Hz, 2H), 2.07 – 1.98 (m, 2H), 1.79 – 1.69 (m, 2H), 0.38 (s, 3H), 0.37 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 206.7, 165.7, 159.1, 137.3, 133.8, 131.7, 131.2, 130.7, 129.3, 129.3, 129.2, 128.0, 127.8, 113.8, 97.3, 82.6, 72.5, 69.4, 63.8, 55.3, 28.9, 25.5, -3.1, -3.2. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.6. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{30}H_{33}BrNaO_4Si$ $[M + Na]^+$ 587.1224; Found 587.1216.

(*R*)-4-(dimethyl(phenyl)silyl)-7-((4-methoxybenzyl)oxy)hepta-2,3-dien-1-yl 4-nitro-benzoate (**6b**)

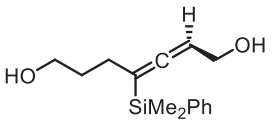


Yellowish oil (100.5 mg, 63% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 8.28 – 8.21 (m, 2H), 8.20 – 8.13 (m, 2H), 7.53 – 7.46 (m, 2H), 7.38 – 7.29 (m, 3H), 7.22 – 7.16 (m, 2H), 6.89 – 6.82 (m, 2H), 5.21 – 5.13 (m, 1H), 4.80 (d, *J* = 7.1 Hz, 2H), 4.36 (s, 2H), 3.80 (s, 3H), 3.41 (t, *J* = 6.5 Hz, 2H), 2.09 – 1.99 (m, 2H), 1.80 – 1.70 (m, 2H), 0.38 (s, 3H), 0.38 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 206.7, 164.5, 159.1, 150.5, 137.2, 135.8, 133.8, 130.7, 130.6, 129.3, 129.2, 127.8, 123.5, 113.7, 97.5, 82.3, 72.5, 69.4, 64.6, 55.3, 28.9, 25.5, -3.1, -3.2. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.5. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{30}H_{33}NNaO_6Si$ $[M + Na]^+$ 554.1969; Found 554.1964.

2s´ **7a**

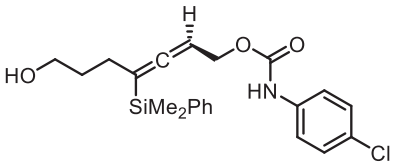
To a stirred solution of the PMB-protected silyl allenol **2s´** (0.12 mmol, 45.9 mg, 1.0 equiv) in DCM (1 mL, 0.1 M) and phosphate buffer (0.1 M, 0.1 mL) was added DDQ (0.18 mmol, 40.9 mg, 1.5 equiv) and the reaction mixture was stirred at r.t. for 2 h. TLC analysis indicated the reaction was complete. Saturated $NaHCO_3$ aqueous solution was added, and the mixture was extracted three times with DCM. The extract was washed with saturated $NaHCO_3$ and brine, and then dried over anhydrous Na_2SO_4. The solvent was removed under reduced pressure and the residue was purified by flash chromatography on silica gel (hexanes/ethyl acetate, 2:1) to afford the corresponding product **7a** as an oil.

(*R*)-4-(dimethyl(phenyl)silyl)hepta-2,3-diene-1,7-diol (**7a**)



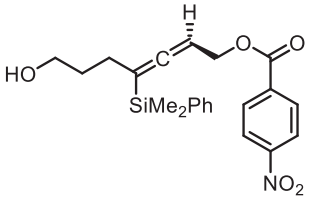
Yellowish oil (22.5 mg, 71% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.55 – 7.50 (m, 2H), 7.39 – 7.34 (m, 3H), 5.13 – 5.07 (m, 1H), 4.07 – 4.02 (m, 2H), 3.59 (td, *J* = 6.5, 1.8 Hz, 2H), 2.10 – 1.98 (m, 2H), 1.92 (s, 2H), 1.76 – 1.61 (m, 2H), 0.39 (s, 6H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 205.7, 137.7, 133.8, 129.3, 127.9, 97.1, 87.3, 62.1, 61.2, 31.5, 25.4, -3.0, -3.2. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.7. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{15}H_{22}NaO_2Si$ $[M + Na]^+$ 285.1281; Found 285.1283.

(*R*)-4-(dimethyl(phenyl)silyl)-7-hydroxyhepta-2,3-dien-1-yl (4-chlorophenyl)carbamate (**5b**)



Following the same procedure for the PMB-deprotection described above. Yellowish oil (51.5 mg, 85% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 7.55 – 7.47 (m, 2H), 7.39 – 7.28 (m, 5H), 7.28 – 7.23 (m, 2H), 6.86 (s, 1H), 5.11 (tt, *J* = 6.8, 3.0 Hz, 1H), 4.71 – 4.55 (m, 2H), 3.60 (td, *J* = 6.5, 1.9 Hz, 2H), 2.12 – 1.94 (m, 2H), 1.75 – 1.64 (m, 2H), 1.59 (s, 1H), 0.39 (s, 3H), 0.38 (s, 3H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 206.5, 153.3, 137.3, 136.6, 133.8, 129.3, 129.0, 128.4, 127.9, 119.8, 97.2, 82.9, 77.3, 77.0, 76.7, 63.6, 62.2, 31.5, 25.2, -3.1, -3.3. ^{29}Si NMR (79 MHz, $CDCl_3$) δ -8.6. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{22}H_{26}ClNNaO_3Si$ $[M + Na]^+$ 438.1263; Found 438.1253.

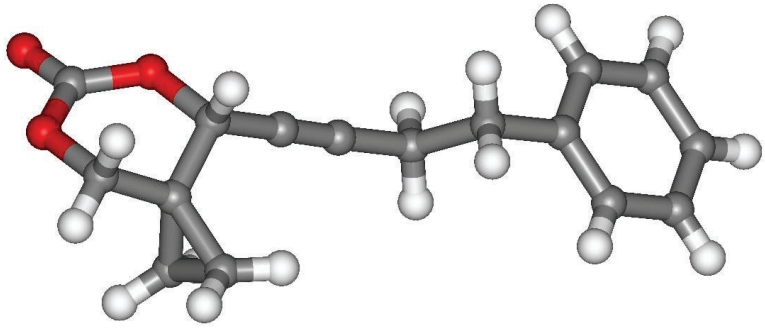
(*R*)-4-(dimethyl(phenyl)silyl)-7-hydroxyhepta-2,3-dien-1-yl 4-nitrobenzoate (**6c**)



Following the same procedure for the PMB-deprotection described above. Yellowish oil (48.0 mg, 93% yield). **^{1}H NMR** (400 MHz, $CDCl_3$) δ 8.30 – 8.23 (m, 2H), 8.21 – 8.15 (m, 2H), 7.53 – 7.47 (m, 2H), 7.37 – 7.30 (m, 3H), 5.19 (tt, *J* = 7.0, 3.0 Hz, 1H), 4.84 (dd, *J* = 7.1, 2.2 Hz, 2H), 3.59 (t, *J* = 6.4 Hz, 2H), 2.10 – 1.99 (m, 2H), 1.72 – 1.63 (m, 2H), 1.57 (s, 1H), 0.39 (s, 3H), 0.38 (s,

4H). **^{13}C NMR** (101 MHz, $CDCl_3$) δ 206.7, 164.6, 150.5, 137.1, 135.7, 133.8, 130.7, 129.4, 127.9, 123.5, 97.5, 82.3, 64.5, 62.2, 31.7, 25.1, -3.2, -3.2. **^{29}Si NMR** (79 MHz, $CDCl_3$) δ -8.5. **HRMS** (ESI/TOF) *m/z* Calcd for $C_{22}H_{25}NNaO_5Si$ $[M + Na]^+$ 434.1394; Found 434.1396.

4.5.5 X-ray molecular structure for 3g'



Procedure: a pure, liquid sample of **3g'** was kept in a freezer at -30 °C for two days and colorless crystals were formed. The measured crystals of **3g'** were stable under atmospheric conditions; nevertheless, they were treated under inert conditions immersed in perfluoro-polyether as protecting oil for manipulation. Data Collection: measurements were made on a Bruker-Nonius diffractometer equipped with an APPEX II 4K CCD area detector, a FR591 rotating anode with CuKα radiation, Montel mirrors and a Kryoflex low temperature device (T = −173 °C). Full-sphere data collection was used with ω and ϕ scans. Programs used: Data collection Apex2 V2011.3 (Bruker-Nonius 2008), data reduction Saint+Version 7.60A (Bruker AXS 2008) and absorption correction SADABS V. 2008−1 (2008). Structure Solution: SHELXTL Version 6.10 (Sheldrick, 2000) was used.21 Structure Refinement: SHELXTL-97-UNIX VERSION.[23]

Crystallographic details for 3g': $C_{16}H_{16}O_3$, M_r = 256.29, orthorhombic, $P2_12_12_1$, a = 5.3269(2) Å, b = 8.8287(3) Å, c = 28.2955(9) Å, α = 90°, β = 90°, γ = 90°, V = 1330.73(8) Å^3, Z =4, ρ = 1.279 mg·M^{-3}, μ = 0.710 mm^{-1}, λ = 1.54178 Å, T = 100(2) K, F(000) = 544, crystal size = 0.20 × 0.10 × 0.05 mm^3, 2θ(min) = 6.248°, 2θ(max) = 135.796°, 37385 reflections collected, 2424 reflections unique (R_{int} = 0.0307), GoF = 1.097, R_1 = 0.0229 and wR_2 = 0.0581 [I>2σ(I)], R_1 = 0.0230 and wR_2 = 0.0582 (all indices), min/max residual density = −0.16/0.09 [e·Å^{-3}], Flack parameter = 0.02(3). CCDC number 2116086.

4.5.6 Experimentally determined and simulated CD spectra of 2s'

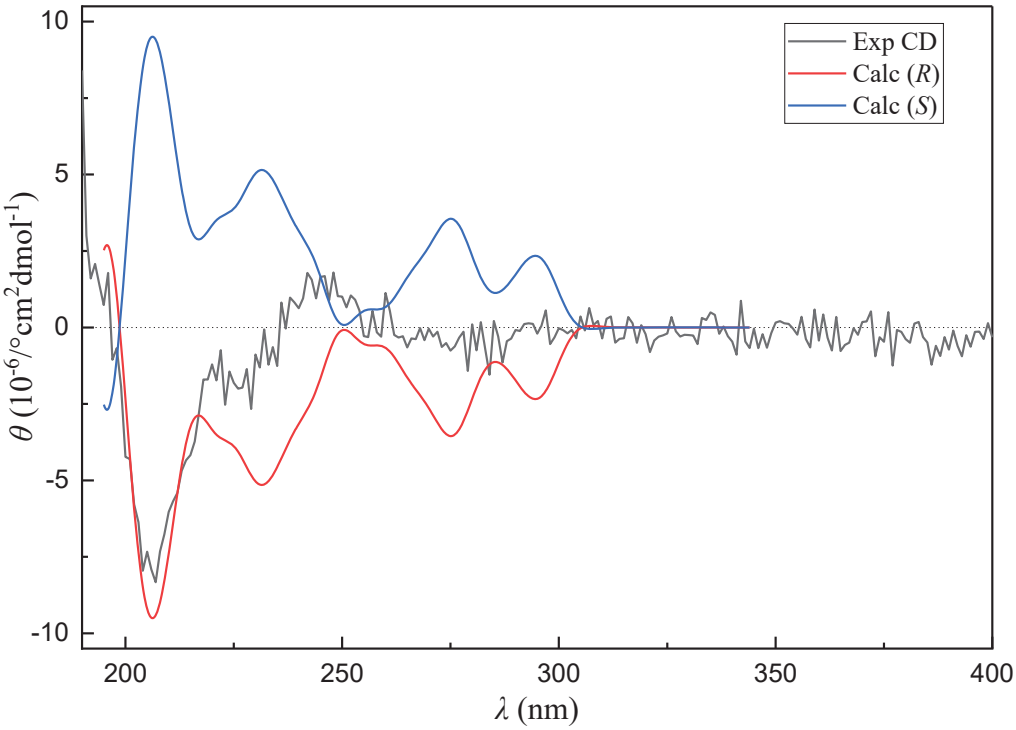


Figure 1. Experimental (*R* enantiomer) and calculated CD spectra (*R* and *S* enantiomer) of **2s'**

Experimental details: The experimental circular dichroism spectrum (CD) of (**2s'**) was recorded at 25 °C on a Chirascan instrument in ACN (4 μg/mL) with a time per point of 0.5 s and triple-data accumulation followed by averaging and manual baseline correction.

Computational details: The geometry of the initial structure of the *R* enantiomer was fully optimized with the double-hybrid DFT method B2PLYP and the def2tzv[14e] basis set, including Grimme's D3BJ dispersion corrections and acetonitrile solvent effects through the implicit model SMD as implemented in Gaussian 16.[24] Then, a molecular dynamics simulation of 50 ps long (4 fs time-step) was performed using the GFN2-xTB[25] method as implemented in xTB, at room temperature and in ACN included using the implicit solvent

model GBSA2. To find the most significant conformations from the molecular dynamics trajectory, we used a clustering process to gather above 1000 structures in 10 clusters via the KMeans[26] clustering method.

For each centre of cluster obtained, the geometry was re-optimized with Gaussian16 at the same level outlined above. From these geometries, the circular dichroism (CD) spectrum was calculated with ADF2019[27] with the SAOP/tzv[28] method and basis set and including acetonitrile via the implicit solvent model COSMO. Each spectrum was based on 100 excitations with an "excellent" numerical grid.

The final averaged CD spectrum was obtained adding the CD of each conformer weighted according to a Boltzmann distribution from the relative potential energies. To compare with the experimental data, a conversion of units was needed from reduced rotatory strength to molar ellipticity.[29,30] Once the conformational space was considered complete, the corresponding CD of the other enantiomer was obtained via a plane reflection. Finally, a shift of the computed CD by –6 nm made a better fitting with experimental data.

4.6 References

1. Nishibayashi, Y. *Synthesis* **2012**, 489. (b) Miyake, Y.; Uemura, S.; Nishibayashi, Y. *ChemCatChem* **2009**, *1*, 342. (c) Ding, C.-H.; Hou, X.-L. *Chem. Rev.* **2011**, *111*, 1914. (d) Francis Adeleke, A.; Brown, A. P. N.; Cheng, L.-J.; Mosleh, K. A. M.; Cordier, C. J. *Synthesis* **2017***, 49,* 790. (e) Sakata, K.; Nishibayashi, Y. *Catal. Sci. Technol.* **2018**, *8*, 12.

2. For illustrative examples see: (a) Nakajima, K.; Shibata, M.; Nishibayashi, Y. *J. Am. Chem. Soc.* **2015**, *137*, 2472. (b) Nishibayashi, Y.; Wakiji, I.; Hidai, M. *J. Am. Chem. Soc.* **2000**, *122*, 11019. (c) Peng, L.; He, Z.; Xu, X.; Guo, C. *Angew. Chem. Int. Ed.* **2020**, *59*, 14270. (d) Watanabe, K.; Miyazaki, Y.: Okubo, M.; Zhou, B.: Tsuji, H.; Kawatsura, M. *Org. Lett.* **2018**, *20*, 5448.

3. (a) Chang, X.; Zhang, J.; Peng, L.; Guo, C. *Nat. Commun.* **2021**, *12*, 299. (b) Gonela, U. M.; Yadav, J. S. *New J. Chem.* **2020**, *44*, 4972. (c) Shemet, A.; Carreira, E. M. *Org. Lett.* **2017**, *19*, 5529. (d) Cai, A.; Kleij, A. W. *Angew. Chem. Int. Ed.* **2019**, *58*, 14944. (e) Gómez, J. E.; Guo, W.; Gaspa, S.; Kleij, A. W. *Angew. Chem. Int. Ed.* **2017**, *56*, 15035.

4. (a) Hattori, G.; Sakata, K.; Matsuzawa, H.; Tanabe, Y.; Miyake, Y.; Nishibayashi, Y. *J. Am. Chem. Soc.* **2010**, *132*, 10592. (b) Cheettu Ammal, S.; Yoshikai, N.; Inada, Y.; Nishibayashi, Y.; Nakamura, E. *J. Am. Chem. Soc.* **2005**, *127*, 9428. (c) Matsuzawa, H.; Miyake, Y.; Nishibayashi, Y. *Angew. Chem. Int. Ed.* **2007**, *46*, 6488.

5. Tsuji, H.; Kawatsura, M. *Asian J. Org. Chem.* **2020**, *9*, 1924, and references cited herein.

6. For some examples: (a) Daniels, D. S. B.; Thompson, A. L.; Anderson, E. A. *Angew. Chem. Int. Ed.* **2011**, *50*, 11506. (b) Huang, X.; Wu, S.; Wu, W.; Li, P.; Fu, C.; Ma, S. *Nat. Commun.* **2016**, *7*, 12382. (c) Motoyama, K.; Ikeda, M.;

Miyake, Y.; Nishibayashi, Y. *Eur. J. Org. Chem.* **2011**, 2239. (d) Lu, F.-D.; Liu, D.; Zhu, L.; Lu, L.-Q.; Yang, Q.; Zhou, Q.-Q.; Wei, Y.; Lan, Y.; Xiao, W.-J. *J. Am. Chem. Soc.* **2019**, *141*, 6167.

7. (a) Miyazaki, Y.; Zhou, B.; Tsuji, H.; Kawatsura, M. *Org. Lett.* **2020**, *22*, 2049. (b) Oelke, A. J.; Sun, J.; Fu, G. C. *J. Am. Chem. Soc.* **2012**, *134*, 2966. (c) Shao, X. B.; Zhang, Z.; Li, Q. H.; Zhao, Z. G. *Org. Biomol. Chem.* **2018**, *16*, 4797. For a review on this topic, see ref. 5. For relevant other work: (d) Jin, Y.; Wen, H.; Yang, F.; Ding, D.; Wang, C. *ACS Catal.* **2021**, *11*, 13355.

8. Guo, K.; Kleij, A. W. *Org. Lett.* **2020**, *22*, 3942.

9. Guo, K.; Kleij, A. W. *Angew. Chem. Int. Ed.* **2021**, *60*, 4901.

10. Luo, Y.; Gutiérrez-Bonet, A.; Matsui, J. K.; Rotella, M. E.; Dykstra, R.; Gutierrez, O.; Molander, G. A. *ACS Catal.* **2019**, *9*, 8835.

11. Ni-catalyzed silylation in a different context has been report-ed, see: (a) Zarate, C.; Nakajima, M.; Martin, R. *J. Am. Chem. Soc.* **2017**, *139*, 1191. (b) Balakrishnan, V.; Murugesan, V.; Chindan, B.; Rasappan, R. *Org. Lett*. **2021**, *23*, 1333.

12. (a) Colvin, E. W.; König, W. A.; Loreto, M. A.; Rowden, J. Y.; Tommasini, I. Bioorg. Med. *Chem. Lett.* **1993**, *3*, 2405. (b) Danheiser, R. L.; Carini, D. J.; Kwasigroch, C. A. *J. Org. Chem.* **1986**, *51*, 3870. (c) Trost, B. M.; Tour, J. M. *J. Org. Chem.* **1989**, *54*, 484. (d) Komiyama, T.; Minami, Y.; Hiyama, T. *ACS Catal.* **2017**, *7*, 631. (e) Wilkinson, J. R.; Nuyen, C. E.; Carpenter, T. S.; Harruff, S. R.; Van Hoveln, R. *ACS Catal.* **2019**, *9*, 8961. (f) Feng, J.-J.; Mao, W.; Zhang, L.; Oestreich, M. *Chem. Soc. Rev.* **2021**, *50*, 2010.

13. (a) Ohmiya, H.; Ito, H.; Sawamura, M. *Org. Lett.* **2009**, *11*, 5618. (b) Hazra, C. K.; Oestreich, M. *Org. Lett*. **2012**, *14*, 4010. (c) Wang, M.; Liu, Z.-L.; Zhang, X.; Tian, P.-P.; Xua, Y.-H.; Loh, T.-P. *J. Am. Chem. Soc*. **2015**, *137*, 14830. (d) Chang, X.-H.; Liu, Z.-L.; Luo, Y.-C.; Yang, C.; Liu, X.-W.; Da, B.-C.; Li, J.-J.; Ahmad, T.;

Loh, T.-P.; Xu, Y.-H. *Chem. Commun.* **2017**, *53*, 9344. (e) Yokobori, U.; Ohmiya, H.; Sawamura, M. *Organometallics* **2012**, *31*, 7909. (f) Yang, L.-L.; Ouyang, J.; Zou, H.-N.; Zhu, S.-F.; Zhou, Q.-L. *J. Am. Chem. Soc.* **2021**, *143*, 6401 (g) Liu, Z.-L.; Yang, C.; Xue, Q.-Y.; Zhao, M.; Shan, C.-C.; Xu, Y.-H.; Loh, T.-P. *Angew. Chem. Int. Ed*. **2019**, *58*, 16538. (h) Xu, Y.; Yi, H.; Oestreich, M. *Organometallics* **2021**, *40*, 2194. (i) Suginome, M.; Matsumoto, A.; Ito, Y. *J. Org. Chem.* **1996**, *61*, 4884.

14. For some selected examples: (a) Kessler, S. N.; Bäckvall, J.-E. *Angew. Chem. Int. Ed*. **2016**, *55*, 3734. (b) Yang, M.; Yokokawa, N.; Ohmiya, H.; Sawamura, M. *Org. Lett*. **2012**, *14*, 816. (c) Uehling, M. R.; Marionni, S. T.; Lalic, G. *Org. Lett*. **2012**, *14*, 362. (d) Ruchti, J.; Carreira, E. M. *Org. Lett.* **2016**, *18*, 2174. (e) Scheipers, I.; Mück-Lichtenfeld, C.; Studer, A. *Angew. Chem. Int. Ed.* **2019**, *58*, 6545. (f) Kobayashi, Y.; Takashima, Y.; Motoyama, Y.; Isogawa, Y.; Katagiri, K.; Tsuboi, A.; Ogawa, N. *Chem. Eur. J.* **2021**, *27*, 3779. (g) Wu, S.; Huang, X.; Fu, C.; Ma, S. *Org. Chem. Front*. **2017**, *4*, 2002.

15. (a) Tollefson, E. J.; Hanna, L. E.; Jarvo, E. R. *Acc. Chem. Res.* **2015**, *48*, 2344. (b) Lucas, E. L.; Jarvo, E. R. *Nat. Rev. Chem.* **2017**, *1*, 0065. (c) Xu, J.; Bercher, O. P.; Talley, M. R.; Watson, M. P. *ACS Catal.* **2021**, *11*, 1604.

16. The justification for these conditions is based on (our) pre-vious findings in Cu-catalyzed propargylic substitutions, see refs. 8, 9 and 13.

17. Ma, G.; Song, G.; Li, Z. H. *Phys. Chem. Chem. Phys.* **2017**, *19*, 28313.

18. Cheng, J.-K.; Loh, T.-P. *J. Am. Chem. Soc.* **2015**, *137*, 42.

19. Tang, X.; Woodward, S.; Krause, N. *Eur. J. Org. Chem.* **2009**, 2836.

20. (a) Mortensen, M. S.; Osbourn, J. M.; O'Doherty, G. A. *Org. Lett.* **2007**, *9*, 3105. (b) Crimmins, M. T.; DeBaillie, A. C. *J. Am. Chem. Soc.* **2006**, *128*, 4936. (c) Bassetti, M.; D'Annibale, A.; Fanfoni, A.; Minissi, F. *Org. Lett.* **2005**, *7*, 1805. (d)

Li, X.; Zhang, M.; Shu, D.; Robichaux, P. J.; Huang, S.; Tang, W. *Angew. Chem. Int. Ed.* **2011**, *50*, 10421.

21. (a) Sirotkina, J.; Grigorjeva, L.; Jirgensons, A. *Eur. J. Org. Chem.* **2015**, 6900. (b) Kleinbeck, F.; Fettes, G. J.; Fader, L. D.; Carreira, E. M. *Chem. Eur. J.* **2012**, *18*, 3598. (c) Röhrle, A. N.; Schmidhammer, H. *Helv. Chim. Acta* **1998**, *81*, 1070.

22. Chang, X.-H.; Liu, Z.-L.; Luo, Y.-C.; Yang, C.; Liu, X.-W.; Da, B.-C.; Li, J.-J.; Ahmad, T.; Loh, T.-P.; Xu, Y.-H. *Chem. Commun.* **2017**, *53*, 9344.

23. Sheldrick, G. M. SHELXTL Crystallographic System, version 6.10; Bruker AXS, Inc.: Madison, WI, **2000**.

24. Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Scalmani, G.; Barone, V.; Petersson, G. A.; Nakatsuji, H.; Li, X.; Caricato, M.; Marenich, A. V.; Bloino, J.; Janesko, B. G.; Gomperts, R.; Mennucci, B.; Hratchian, H. P.; Ortiz, J. V.; Izmaylov, A. F.; Sonnenberg, J. L.; Williams; Ding, F.; Lipparini, F.; Egidi, F.; Goings, J.; Peng, B.; Petrone, A.; Henderson, T.; Ranasinghe, D.; Zakrzewski, V. G.; Gao, J.; Rega, N.; Zheng, G.; Liang, W.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.; Nakai, H.; Vreven, T.; Throssell, K.; Montgomery Jr., J. A.; Peralta, J. E.; Ogliaro, F.; Bearpark, M. J.; Heyd, J. J.; Brothers, E. N.; Kudin, K. N.; Staroverov, V. N.; Keith, T. A.; Kobayashi, R.; Normand, J.; Raghavachari, K.; Rendell, A. P.; Burant, J. C.; Iyengar, S. S.; Tomasi, J.; Cossi, M.; Millam, J. M.; Klene, M.; Adamo, C.; Cammi, R.; Ochterski, J. W.; Martin, R. L.; Morokuma, K.; Farkas, O.; Foresman, J. B.; Fox, D. J. Gaussian 16 Rev. A.03, Wallingford, CT, **2016**.

25. Bannwarth, C.; Caldeweyher, E.; Ehlert, S.; Hansen, A.; Pracht, P.; Seibert, J.; Spicher, S.; Grimme, S., *WIREs Comput Mol Sci.* **2021**, *11*, e1493.

26. Jin, X.; Han, J., K-Means Clustering. In *Encyclopedia of Machine Learning*, Sammut, C.; Webb, G. I., Eds. Springer US: Boston, MA, **2010**; pp 563.

27. Te Velde, G.; Bickelhaupt, F. M.; Baerends, E. J.; Fonseca Guerra, C.; van Gisbergen, S. J. A.; Snijders, J. G.; Ziegler, T., *J. Comput. Chem.* **2001**, *22*, 931.

28. Pintre, I. C.; Pierrefixe, S.; Hamilton, A.; Valderrey, V.; Bo, C.; Ballester, P., *Inorg. Chem.* **2012**, *51*, 4620.

29. Stephens, P. J.; Harada, N., *Chirality* **2010**, *22*, 229.

30. Makkonen, E.; Rossi, T. P.; Larsen, A. H.; Lopez-Acevedo, O.; Rinke, P.; Kuisma, M.; Chen, X., *J. Chem. Phys.* **2021**, *154*, 114102.

General Conclusions

The main objective of this doctoral thesis was to develop new applications for silylborane and diborane reagents combining them with highly versatile and modular internal alkyne-substituted cyclic carbonates using cheap and abundant metal catalysts (i.e., Cu and Ni). With these new approaches, we prepared a set of silyl allenols including enantioenriched ones and highly stereo-controlled di-boron compounds, which can be potentially in Hiyama or Suzuki coupling reactions towards the synthesis of more complex molecules useful in the context of pharmaceutical development and/or materials science.

In **chapter 2**, we designed a general procedure for the preparation of highly versatile and modular internal alkyne-substituted cyclic carbonates. Then, we developed an efficient and mild Cu-catalyzed protocol for the decarboxylative silylation of these functionalized carbonates affording 2,3-allenols featuring four different substituents. This practical methodology provides access to a wide scope of tetrasubstituted, functionalized allenes in excellent yields.

In **chapter 3**, we further exploited the application of the internal alkyne-substituted cyclic carbonates. We developed a mild Cu-mediated methodology that allowed for dichotomic borylation of alkynyl-substituted carbonates, affording either 1,2-diborylated 1,3-dienes or α-hydroxy allenes as the principal products. The chemoselective outcome depended on the nature of the diboron(4) reagent. Through a series of control experiments and spectroscopic/crystallographic data, we proposed a mechanistic rationale which aligns with a crucial role of the relative kinetics of the second borylation step versus *i*-PrOH-assisted protodemetalation.

In **chapter 4**, we devised a practical procedure for the wide-scope synthesis of enantio-enriched, internal alkyne-substituted five- and six-membered cyclic carbonates. We developed a Ni-mediated decarboxylative silylation of alkynyl cyclic carbonates affording a wide range of highly substituted 2,3- and 3,4-allenol products in good yields. The formal cross-coupling between a tentative intermediate Ni(allenyl) and the silyl reagent was

further extended to enantiospecific conversions providing access to chiral allene synthons. This protocol marked, as far as we know, the first Ni-catalyzed propargylic silylation proceeding through an S_N2' manifold. Importantly, we believe that the Ni^0-mediated oxidative addition of the carbonate onto the zero-valent metal is a crucial step setting the system up for the substitution process. This is contrary to Cu-mediated silylation which proceeds through well-known β-oxygen elimination, which is unprecedented in Ni-catalysis.

Altogether, the **general conclusion** from this thesis work (based principally on the developed organic methodologies) is that a new dawn has risen for specially functionalized cyclic carbonates. Whereas vinyl cyclic carbonates have already conquered a prominent position as privileged substrates in allylic substitution chemistry and [3 + n] and [5 + n] cycloaddition reactions, other types of carbonates such as the alkynyl-substituted ones presented in this doctoral work have only recently emerged as precursors with great synthetic potential. We therefore foresee that a further amplification of the synthetic use of these functionalized cyclic carbonates from vinyl to alkynyl- and allenyl-substituted ones. This represents an attractive future development being inspirational for the communities with a focus on fine-chemical and pharmaceutical synthesis that requires exquisite control over the chemo-, regio-, stereo- and/or enantio-selectivity.

UNIVERSITAT
ROVIRA i VIRGILI